Reliability Constrained Optimal Investment in a Microgrid with Renewable Energy, Storage, and Smart Resource Management

A Thesis Submitted to the

College of Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of Master of Science

in the Department of Electrical Engineering

University of Saskatchewan

Saskatoon

By

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ABSTRACT

Environmental concerns have led to a rapid increase in renewable energy development and production as the global demand for electricity continues to increase. The intermittent and uncertain nature of electricity generation from renewable sources, such as wind and solar, however, create significant challenges in maintaining power system reliability at reasonable costs. Energy storage and smart-grid technologies are perceived to provide potential solutions to these challenges in modern power systems of different sizes. This work investigates the opportunity to incorporate energy storage in microgrids with renewable energy production, as well as applying smart microgrid management techniques to reduce the lifetime costs while maintaining an acceptable level of reliability.

A microgrid consisting of a 5 home community with generation supplied by two propane generators to meet the "N-1" reliability criterion is used as the base case scenario. Actual load data of typical homes is obtained from the industry partner. An equivalent loss of load expectation criterion is used to benchmark the acceptable reliability level. A model is developed to calculate the lifetime operational cost of the base case scenario which is used to assess the benefit of the addition of renewable energy sources, energy storage, and smart microgrid management techniques.

A MATLAB program is developed to assess the 20 year operational costs of various combinations of renewable energy sources and battery energy storage, which will be considered the lifetime of the system. The combination of generation and storage which yields the lowest lifetime operational cost is defined as the optimized microgrid, and is used as a basis to determine

if additional savings are realized by the implementation of a microgrid operated by a Smart Microgrid Management System (SMMS).

The conceptual layout of the proposed SMMS is presented along with identified methods of utilizing in-home thermal storage. The SMMS mechanism is discussed along with proposed functionality, potential methods of employment, and associated development and implementation costs. The microgrid operated by the SMMS is assessed, and its lifetime operational cost is presented and contrasted against the base case microgrid and the optimized microgrid.

A power system reliability evaluation of the proposed microgrids are conducted using a probabilistic method to ensure that reliability is not sacrificed by the implementation of a cost-minimized microgrid. A sequential Monte Carlo simulation model is developed to assess the power system reliability of the various microgrid configuration cases. The functionality of this model is verified using an existing reliability assessment program.

The results from the presented studies show that the implementation of renewable energy sources, energy storage, and smart microgrid management techniques are an effective way of reducing the operational cost of a remote microgrid while increasing its power system reliability.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the dedicated effort of a large number of people. I would like to express my sincerest thanks to my supervisor, Dr. Rajesh Karki for the valuable guidance, insight, and encouragement I received throughout my research work. Special thanks are due to the Saskatchewan Research Council for providing time, expertise, and funding to perform this research, and for providing the research objectives and resources to carry out the study. Specifically, I would like to thank Michael Sulatisky, Nathan Peter, Chris James, Sheldon Hill, Craig Murray, and Kelly Winder for their input and review throughout this research.

I would also like to offer gratitude to Darryl Jessie of Raum Energy, and Jami Manastyrski of Check-It Solutions for providing data and guidance for this project, and the Engage Grant provided by NSERC to support industry engagement.

I would like to acknowledge the College of Graduate Studies and Research, and the Department of Electrical and Computer Engineering for their provision of laboratory equipment and resources. As well, thank you to my committee members for their valuable suggestions and review of my thesis.

Finally, and most importantly, I would like to thank my loving wife, Pamela, and my wonderful children, Alexa and Fynn, for their love, support, encouragement, and gift of time that has allowed me to complete this important research.

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List of Abbreviations

DSM	Demand Side Management
CLS	Curtailable Load Shedding
GSHP	Ground Source Heat Pump
IIT	Illinois Institute of Technology
kW	Kilowatt
kWh	Kilowatt Hours
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
OEM	Original Equipment Manufacturer
PHEV	Plug-In Hybrid Electric Vehicles
PLC	Programmable Logic Controller
PV	Photovoltaic
RBTS	Roy Billinton Test System
SCADA	Supervisory Control and Data Acquisition
SIPSREL	Small Isolated Power System Reliability
SMCS	Sequential Monte Carlo Simulation
SMMS	Smart Microgrid Management System
SOC	State Of Charge
SRC	Saskatchewan Research Council

1. INTRODUCTION

1.1. Introduction to Microgrids

A microgrid is a set of electrical power generation sources that are networked together to meet the energy needs of a localized community, but may also maintain a single connection point to a larger electrical grid [1]. Microgrids are typically large institutions such as prisons, hospitals, universities, etc., but they can also be small communities, or even single residence dwellings [2].

Microgrids characteristically have a high level of reliability when connected to a macrogrid and contribute to a greater reliability of the macrogrid as a whole [3]. A microgrid requires some level of power management when operating independently to ensure that its power supply can meet all of the internal load demands, or at least some critically identified loads. The management of energy generation and consumption by applying automation driven by relevant data acquired and processed using monitoring systems is often referred to as a "smart grid" application.

Microgrids are becoming increasingly popular as a form of distributed power generation typically employing renewable energy [4]. This is largely due to the improving economic viability of renewable energy sources [5], the interest in improved sustainability, and the desire to increase distributed generation to reduce loading on over-capacity distribution lines [6].

The focus of this study is to evaluate the potential benefit of system intelligence applied to a microgrid. In addition, this dissertation provides some direction on the potential market for microgrids and associated smart power management systems.

1.2. Microgrids with Renewable Energy

Microgrids present unique niche opportunities to incorporate renewable energy. Often, the peak load of a microgrid is quite limited depending on the size of the system. When considering a small peak load (such as below 100 kW), the economics present are rather different than that of a large utility grid. On a large-scale such as a large utility grid, it is difficult for renewable energy with incentives to be cost-competitive with natural gas and coal generation stations, especially once reliability, lifetime, and capacity factor are considered. For instance, according to the United States Energy Information Agency the levelized capital cost of a conventional combined cycle natural gas generation system in the United States is $15.8 / MWh and its lifetime levelized cost is $67.10 / MWh [7]. In comparison, the levelized capital cost of terrestrial wind generation is $70.30 / MWh, and its lifetime levelized cost is $86.60 / MWh. The initial investment for natural gas generation is only 22.5% of the investment compared to wind generation, and its lifetime cost is 77.5% of the cost of wind generation. In addition, natural gas-fired generation is dispatchable and has an 87% capacity factor compared to a 34% capacity factor typical of wind turbines. In support of this, Aboriginal Affairs and Northern Development Canada indicate that the levelized cost of wind generation is 29% greater than conventional combined cycle natural gas generation [8].

In contrast to large-scale utility grids, the economics for renewable energy integration can be quite different when considered for small-scale microgrids. Often, the reasons for developing a microgrid are financially motivated, whether it be to offset fossil fuel consumption that must be delivered to remote locations by ice road or airplane, or to reduce reliance upon a utility-power grid with prohibitively high electricity rates. [9]

A study performed by Rehman and Al-Hadhrami [10] found that microgrids consisting only of diesel generators were cost-competitive when fuel prices were below \$0.60 / L, however, renewables such as solar became more economical when fuel prices exceeded \$0.80 / L. Solar penetration, or the ratio of installed solar generation capacity to the total installed generation power capacity of the system, as high as 21% was found to be economically beneficial in the study. Although higher degrees of penetration were tested, a growing amount of unutilized energy rendered the system uneconomical.

A renewable energy planning study conducted by Hafez and Bhattacharya [11] indicated that the net present cost of a diesel-renewable mixed microgrid was lower than alternative options including a fully renewable-based microgrid, and a stand-alone diesel-based microgrid. As such, there exists a diesel-renewable balance for a small microgrid where the lifetime cost of the system is lower than alternative options including a fully renewable microgrid, and a stand-alone diesel-based microgrid.

A paper written by Weis and Ilinca [12] considered the potential for wind energy incorporated in to Canadian remote communities along with energy storage. They found that depending on the cost of fuel, energy storage, and wind generators, a viable business case can be developed when annual wind speeds are in excess of 6.0 m/s for wind generators only, and wind generators with energy storage become viable as annual wind speeds approach 7.0 m/s as long as the cost of energy storage systems is less than \$1,000 / kW. In the case of wind energy storage systems, the wind turbine array could be sized to produce an additional 50% of energy to the microgrid.

A paper written by Billinton and Karki [13] explored the reliability detriments of meeting additional system load by installing renewable generation rather than traditional diesel units in an off-grid application. It was determined that the most cost-effective method of expanding a microgrid's generation portfolio was by adding wind-diesel systems as needed, provided the unit and installation cost of the wind turbine was approximately $1,950 / kW, and the cost of photovoltaics (PV) was $11,000 / kW. The wind generators were used to minimize diesel consumption, while the diesel generators provided the specified level of reliability to the microgrid. It is important to note that as of 2012, the average turnkey cost of grid-connected solar ranged from $2.80 / W to $5.00 / W, while the average turnkey cost of off-grid system is $8.10 / W [14].

A study developed by Alawi and Islam [15] discussed using demand-side management (DSM) techniques to modify the energy consumption of consumers in order to smooth daily load peaks and valleys. The study generated load profiles from first principles using diversified demand data. The resultant calculations determined that by using DSM techniques, the generation components for a small off-grid community could be reduced by up to 20%, and the addition of photovoltaic generation could be used to optimize the size of a diesel generator reducing the cost of the entire test system. The community in this study consisted of six homes in the Middle East region, similar to what is being considered in this study.

Hu, Karki, and Billinton [16] studied the effect of adding energy storage to a grid characterized by the Roy Billinton Test System (RBTS) [17]. A sequential Monte Carlo Simulation (MCS) was used to conduct a reliability evaluation of generating systems including wind and energy storage. Energy storage was used in three possible operating scenarios:

1. Stored energy was dispatched only when the summation of available wind power and conventional power did not meet the system load.
2. Energy storage was used only to supplement wind power when it was less than a certain percentage of the system load.

3. Energy storage was used to supplement wind power to meet a certain percentage of the system load as well as to supplement conventional power if the system load is not met, thereby supporting conventional generating units to avoid load curtailment while meeting the stability criterion.

The authors found that Scenario 1 maintained the highest degree of reliability, and was capable of reducing the loss of load expectation (LOLE) from 0.75 hours / year to 0.55 hours / year. The other two scenarios were used to store wind energy and avoid curtailment as well as improve reliability. An optimal operating strategy for energy storage has been investigated in this work with an objective of minimizing lifetime system cost at an acceptable reliability level.

Eriksen, et al [18] have shown that many European countries have achieved high levels of renewable penetration, most notably Denmark. At lower levels of penetration, wind power can be treated as negative load and does not cause significant grid instability, however, at high levels of wind power penetration difficulties arise since wind turbine generators cannot be reliably scheduled in contrast to traditional generation facilities. Wind forecasting is required to aid in the prediction of wind turbine generation adequacy at higher levels of penetration where aggregate capacity is projected between 1 – 48 hours into the future, and aids in scheduling long-term balancing power reserves.

Black and Strbac [19] studied the value of storage pertaining to a 26 GW generation from various sources characteristic of the system in Great Britain and found that using energy storage to provide standing reserve allowed decreased wind energy curtailment and reduced the required energy generation by conventional plants, thus reducing fuel costs.

Research performed by Keane et al [20] applied DSM techniques and found them to be valuable in assessing reserve on a utility grid. Customer demand-response methods consisted of altered demand profile, load shifting demand, and curtailment. The peak demand was reduced by 5.5% - 6.5% during the summer and winter, and the overall reduction in energy was 4% per year. These methods have been studied and appropriate DSM techniques are employed in this study.

In a study that considered energy management systems in microgrid operations, Su and Wang [21] discusses how microgrids have shifted from prototype demonstration projects to full-scale commercial deployment to address reliability challenges associated with aging infrastructure and increased loads. Distributed energy storage was discussed as a method to make microgrids more cost-effective by absorbing excess energy, or supplying energy during peak loads or when the load exceeds the available generation capacity. Demand-side management of controllable loads based on real-time set points was also considered to increase the efficiency of the microgrid network.

An article published by Burr [22] shows that microgrids have become an economically viable option compared to being connected to the utility. Some microgrids, such as present at the United States Food and Drug Administration are seeing payback periods on the order of 10 years at normal operation. This payback is hastened when grids are susceptible to frequent power outages or during natural disasters such as Hurricane Sandy in 2012.

A paper written by Huang, Lu, and Zhang [23] considered crucial aspects that would dictate the success and acceptance of microgrids. Features such as intelligence that allows microsource generators to be added in a "plug and play" manner, and a master controller which regulates multiple slave controllers to alleviate congestion and simplify operation. The latter characteristic was further developed and employed in the algorithm proposed in this project.

Kyriakarakos et al [24] discussed using controller agents to monitor and operate loads according an intelligent DSM system program, and found that this was a beneficial method of performing DSM within a microgrid. The author had proposed four agents that would control the power line to each of the following categories of load:

- Lighting
- Refrigeration (fridge and freezer)
- Various consumptions (appliances, electronics devices, etc)
- Space heating / cooling

Kriett and Salani [25] proposed a grid-connected microgrid complete with combined heat and power generation, as well as solar thermal and photovoltaic generation, thermal and electrical energy storage, thermal dumps, and residential electrical loads, some of which were controlled by the microgrid control system. By utilizing the developed optimal control system, the authors were able to reduce annual operating costs by between 3.1% and 6.2% compared to the original annual operating costs of a well-equipped residential microgrid. Characteristics of the efficient control system included optimal storage control and optimal demand side management.

A hot water heater study conducted by Paull, Li, and Chang [26] used a multi-object DSM program to remotely control domestic hot water heaters. The purpose of the study was to increase power system efficiency and reliability. The authors found that controlling the hot water heaters in an aggregate manner adversely affected users, thus, individual control of water heaters was recommended. The resultant program had negligible effects on users, while providing peak shaving, frequency regulation, synchronous reserve, and other benefits.

A paper written by Lasseter [27] discussed the use of microsource controllers capable of responding to setpoints within milliseconds. The microsource controller uses local information regarding electrical requirements, energy costs, DSM requests, and special grid needs to control the source directly, alleviating the need for source-to-source communication. Moreover, this opens the gateway to plug-and-play operation causing multiple sources to be added to a microgrid without the need to alter the controller, or update existing microsource software.

Energy storage as it pertains to plug-in hybrid electric vehicles (PHEVs) is also being considered as a method for increasing the penetration of renewable technologies on to electrical grids. A paper published by Hakimi and Moghaddas-Tafreshi [28] compared two scenarios of using PHEVs on a microgrid with renewable energy. The first scenario consisted of using the PHEVs in a “plug-and-forget” manner where no active charging management was used. The system’s load factor for the first scenario was 0.58 and renewable energy was used to deliver approximately 56% of the required load energy. In the second scenario, an algorithm was used to manage the charge / discharge characteristics of PHEVs to increase renewable energy penetration and smooth out daily load curve variations. The second scenario yielded a load factor of only 0.49 and renewable energy was used to deliver almost 67% of the required energy of the load. Thus, by applying an algorithm, increased renewable penetration was achieved, while reducing the load factor.

1.3. Microgrid Reliability

A move towards distributed generation has taken place to meet concentrated load requirements and to allow energy to be generated at the site in which it is consumed [29], however, limitations exist for the addition of distributed generation. Firstly, the presence of generation on distribution lines leads to changes in local fault-current characteristics and may require a redesign of the local fault protection system. Secondly, distribution systems are most often radial networks, unlike the mesh networks created by transmission systems, and little redundancy exists which impedes reliability [30]. Thirdly, distribution lines tend to have high resistance which increases issues with voltage drop and line losses [31]. Lastly, a general lack of communication and Supervisory Control and Data Acquisition (SCADA) systems limit the amount of feedback and thus the ability to control the grid becomes difficult [32].

Microgrids are contrasted from distributed generation in that they can be regarded as both scheduled load from the perspective of the utility, and flexible power sources from the perspective of consumers [33]. In addition, flexible microgrids have the ability to operate in user-defined modes such as constant power or load, arbitrage, emergency backup, or islanding operation. Use of a microgrid controller is necessary for the functioning of a flexible microgrid, however, for further effectiveness load controllers are introduced to aid in altering loads through shedding, deferral, or derating [34].

Grid-connected microgrids have been shown to increase the reliability of electrical systems, both at the macrogrid level, and within the microgrid [35]. This is intuitive, as the microgrid is able to shed load and operate autonomously when required by the macrogrid to benefit its reliability. Likewise, if the macrogrid experiences a forced outage, the microgrid is able to be isolated and operate autonomously until the macrogrid regains operations. It appears that microgrids will also be required to play a key role in sustaining macrogrid reliability as demand for load continues to grow. Despite the ever-increasing efficiency of appliances and consumer products, electrical consumption per capita continues to rise [36]. At the current rate of growth, it appears unlikely that macrogrids will be capable of expanding at the required rate to ensure a high degree of grid reliability. Microgrids currently in operation such as that of The Perfect Power microgrid at the Illinois Institute of Technology (IIT) have been shown to reduce outages, minimize electrical disturbances, reduce greenhouse gas emissions, defer substation upgrades, and reduce the campus' peak demand [37]. For instance, for the test system studied by Lo Prete, Chiara et al [38] the loss of load expectation (LOLE) [39] of a grid without microgrids present was calculated to be 7.70 hours / decade. With the addition of microgrids to the system, the LOLE decreased to 5.53 hours / decade.

1.4. Problem Definition

Microgrid technology has become more prevalent in the past decade with large microgrids being developed for the purposes of military [40], education [41], and public institutions such as prisons [42]. Microgrids are also being developed to reduce the system cost of energy as it pertains to energy pricing as well as other costing associated with demand rate billing and loss of revenue during power outages.

Many isolated, off-grid communities in Canada are dependent solely on fossil fuel generation [43]. In fact, only 14% of the listed off-grid communities in Canada have a renewable generation component included in their generation portfolio. There are many environmental, social, and economic concerns related to the use of fossil fuel generation, especially as it pertains to use in isolated communities.

Environmental concerns exist regarding the use of fossil fuel generation including the possible risk of spills during transport by airplane, truck, or barge, GHG emissions caused by transportation methods, and possible contamination of soil due to storage fuel tank leaks.

Social concerns include generator noise, local emissions from the generator which could contribute to health concerns, and reliance on a single fuel in a remote community could lead to risk if the fuel source is not available for a period of time, or if stored improperly.

The final concern is regarding financial viability. Fuel costs are not only subject to market price fluctuations, but to additional costs related to transportation, storage, and security which must be taken into account when assessing the cost of generation. Thompson and Duggirala [44] state that the delivered cost of fuel to remote communities can be three times more expensive than fuel prices elsewhere in Canada.

Key criteria for the success of microgrid implementation include correctly sizing storage and generation elements, and developing cost-effective diversified means of generating electricity to ensure an acceptable level of reliability.

In 2011, Raum Energy approached the Saskatchewan Research Council (SRC) with a novel idea of incorporating an energy storage device into their renewable energy generation systems. Raum Energy was a manufacturer and distributor of small, residential wind turbines (< 3.5 kW), and also distributed photovoltaic panels. Initially, the intention was to market an integrated renewable energy generator and storage system to jurisdictions with time of day pricing to take advantage of arbitrage and reduce the payback period associated with the implementation of renewable energy installations. Upon further investigation, opportunities related to microgrid development in isolated communities were identified by both Raum Energy and SRC as they would be potential early adopters of microgrid technology.

Besides determining the sizing characteristics for generation and storage, another key component of microgrid design was identified by the project partners: what effect would a smart microgrid management algorithm have on the financial viability of a microgrid? DSM techniques are widely accepted as cost-effective methods of reducing energy consumption and costs by both customers and suppliers. SRC identified DSM and the potential for utilizing pre-existing energy storage as possible methods for reducing the generation and storage requirements for a microgrid, thereby reducing microgrid costs.

1.5. Research Objective

With the problem definition in mind, the specific objectives of this research project, as defined by our industry partners Raum Energy and SRC, are as follows:

- Determine the load characterization for a small community consisting of 5 homes
- Specify an optimized base case microgrid consisting of energy storage, generation, and loads
- Develop a conceptual design for a smart microgrid management system which monitors and governs the characteristics of energy storage devices, generation systems, and loads within the microgrid.
- Develop an algorithm to model the functionality of the optimized microgrid both with and without the smart microgrid controller to determine if financial benefits exist

In addition to these research objectives, it is beneficial to ascertain the reliability of the developed microgrid model to ensure a high degree of resilience was maintained, especially since the proposed microgrid is isolated from a macrogrid. As such, the reliability of the microgrid is analyzed using loss of load expectation (LOLE) reliability indices [45] and verified using the Small Isolated Power System Reliability (SIPSREL) program [46].

1.6. Thesis Outline

This research work has been divided into six chapters. Chapter 1 introduces the concept of microgrids, and discusses previous research efforts pertaining to the integration of renewables, and the effect on system reliability. Based on this understanding, the problem definition of the industry partners is presented, and objectives are defined to address the industry need. These objectives are the research objectives of this thesis.

The residential load characteristics of the proposed system are presented in Chapter 2, along with details associated with the potential generation sources being considered for this study.

Chapter 3 presents a base case microgrid which operates with no alternative energy generation or energy storage devices. This system is used to compare and contrast the financial benefits that the subsequent models provide. An optimized base case is then developed that employs the use of energy storage, and renewable generation sources, but does not include the employment of an intelligent algorithm. This system employs the use of a developed MATLAB model [47] to optimize the base case's amount of storage and generation. Optimization criteria consists of the lowest operational plus capital cost calculated for each combination of energy storage and generation mix over the specified project lifetime.

Chapter 4 proposes methods of DSM embodied through curtailment as well as load-shifting. An algorithm is developed in MATLAB to incorporate DSM techniques to further reduce the capital and operational costs associated with supplying energy to the community. A conceptual design for the load management system is presented that would enable the operation of advanced DSM techniques for the community, and cost estimates are discussed. Results are discussed, and the lifetime operational costs of the resulting ideal microgrid combination are compared with the previously developed microgrid costs.

In Chapter 5, a Sequential Monte Carlo Simulation model is developed to assess the subsequent reliability of the developed systems. Generation tables for the proposed system are developed as input for an existing reliability program which also assesses reliability. The results of this program are compared against the results from the Sequential Monte Carlo Simulation model.

Chapter 6 summarizes the work completed in this research project and the results, and concludes the thesis.

2. MICROGRID CHARACTERISTICS FOR OPTIMIZATION MODEL DEVELOPMENT

2.1. Introduction

The microgrid analyzed in this project consists of five homes with an integrated combination of electric energy from wind turbine generation, photovoltaic generation, propane generation, and battery energy storage. The load characterization of the five-home system and each of the potential electrical generation and storage components are discussed in the following sections.

2.2. Load Characterization

Real-time residential load profiles obtained from Check-It Solutions [48] are used in this study to obtain realistic load characteristics for typical residential customers. Check-It Solutions is a company founded in Regina, Canada that has developed an affordable, flexible, and customizable method of measuring energy consumption in residential homes. Access to real-time and historical electrical consumption was provided to facilitate the integration of these load profiles into the algorithms that are developed. The individual load profiles are presented in Appendix A.

The data acquisition system installed by Check-It Solutions [48] provided historical energy consumption in hourly increments of energy (kWh) consumed. A few of the residences did not have a complete year of data available for analysis. For these residences, data is extrapolated using previously recorded data that was representative of the missing data. A program is written to divide this hourly data evenly into 15 minute increments to mirror the time increment that is used in the analysis of the power generation from the renewable sources and the energy storage facility in the system.

The overall purpose of obtaining several time-varying load profiles for a diverse group of residences is to analyze how the cumulative time-of-day power demand for the system varies with the addition of multiple residences. A simple stepped load profile estimated for a single home and multiplied to form a 'group' of homes is not representative of the varying time-of-day demands of multiple unique homes. For example, Figure 2.1 indicates the load profile for one of the residences. Over the course of the year its peak load is approximately 7 kW. If this individual load profile were simply scaled, the peak load could be as high as 35 kW, whereas the cumulative peak load for all five homes is only 25 kW as shown in Figure 2.2, a reduction in potential peak load by approximately 30%. This indicates that there is an efficiency gained in combining multiple residences with unique load profiles. This is consistent with diversified load analysis in electrical utilities and is well-understood.

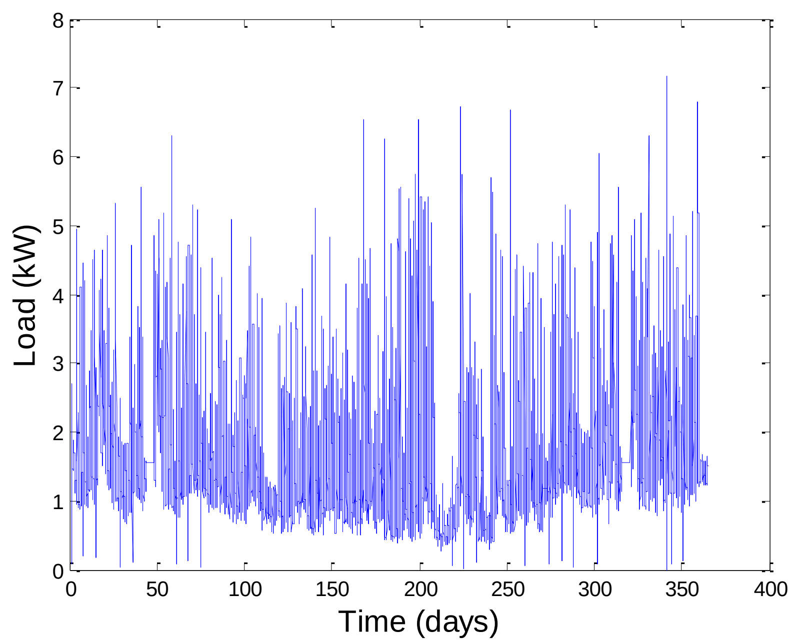

Figure 2.1: Single Residence Annual Load Profile with One Hour Resolution

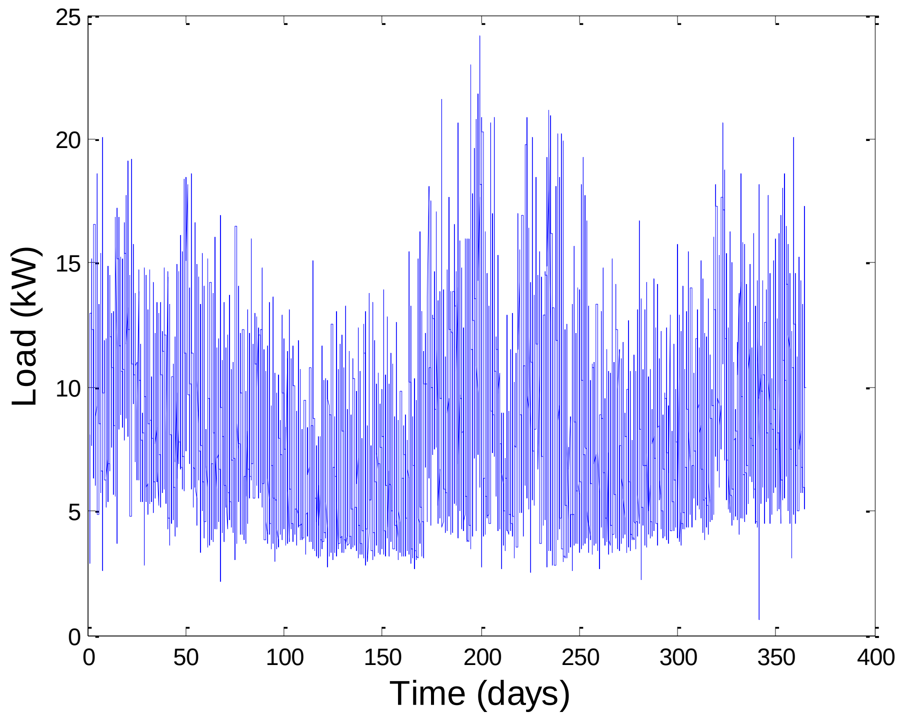

Figure 2.2: Cumulative Annual Load Profile with One Hour Resolution

Although the individual energy consumption of the five monitored homes varies substantially, the average annual energy consumption of the proposed five-home system is 13,807 kWh per home. In comparison, an energy-efficient home located in Saskatchewan has been monitored and found to consume an average of 14,000 kWh per year. This home uses electricity as its sole energy source, and has its own well water supply, and waste management system. It is therefore assumed that the acquired load profiles from Check-It Solutions are indicative of a similarly-designed home with similar characteristics. Table 2.1 shows the individual energy consumption of each of the five monitored homes. A generic descriptor is used to maintain the confidentiality of the residents.

Table 2.1: System Annual Energy Consumption

Descriptor	2011-12 Annual Energy Usage (kWh)
1. Academy	13,384
2. Chatwin	21,454
3. Garnet	5,767
4. Gregory	15,526
5. Struthers	12,902
Mean	**13,807**

Figure 2.3 indicates the load duration curve for the cumulative microgrid.

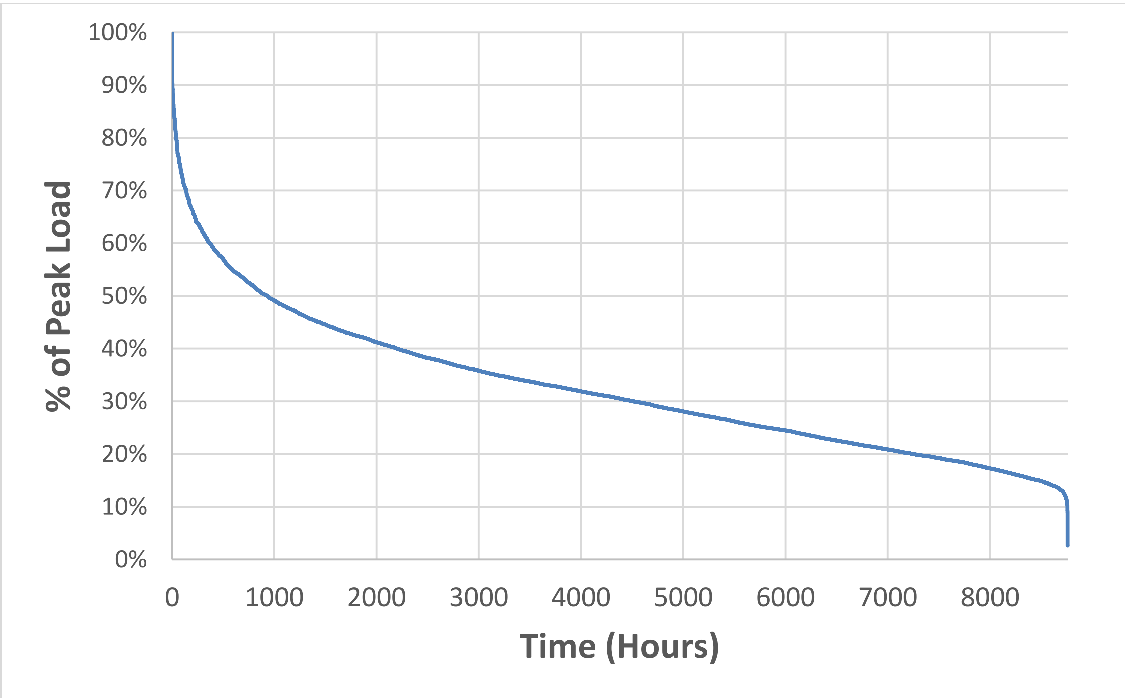

Figure 2.3: Cumulative Load Duration Curve

2.3. Generation and Storage Characteristics

The following portion of the chapter discusses the various electrical generation and electrical storage components that are considered for the development of the base case and optimized base case systems, as well as the optimized microgrid with a smart microgrid management system.

2.3.1. Solar Photovoltaic Generation

The inclusion of photovoltaic generation in the generation combination for the microgrid systems is part of the analysis of this project. Photovoltaic panels have decreased in price by approximately 70% in the past ten years due to in an increase in manufacturing efficiencies, consumer demand, and increased collector electrical conversion efficiency. As such, many small-scale renewable energy installations include photovoltaic arrays.

A quotation for the supply and installation of a 10.42 kW array was received from a local consultant that specializes in the distribution and installation of solar panels, as well as the design and fabrication of single axis solar trackers. The total cost of the system is $42,450. This includes equipment, electrical, installation, and foundation work. This is an installed cost of $4,170/kW, and an equivalent energy cost of $0.16/kWh over the lifetime of the panels. The solar panels carry a 25 year warranty. An example of a similar photovoltaic system is shown in Figure 2.4.

Figure 2.4: 8.19 kW Solar Array [49]

The local consultant also provided an annual energy profile for the electrical production of an 8.19 kW array. The total annual production of the array is 10,690 kWh, and the capacity factor is 14.9%. The annual energy production of the array was recorded using a Bluetooth data logger at ten minute increments. A computer program is written to aggregate this energy production over a 30 minute period, and then divide the production evenly between two 15 minute periods to mirror the time step that is used to analyze the other forms of generation.

2.3.2. Wind Energy Generation

Wind turbine generation has become an increasingly common option for rural residents to generate their own power over the past 15 years, and is also included in the analysis. Figure 2.5 shows a 3.5 kW wind turbine manufactured by Raum Energy.

Figure 2.5: Raum 3.5 kW Wind Turbine [50]

Although an annual generation profile for the 3.5 kW wind turbine is not available, the Saskatchewan Research Council has done extensive monitoring of wind resources at numerous sites across Saskatchewan. A full year of wind speed data collected on a per-minute basis was available from an installed site near Dalmeny, SK. This site is close to the site from where the solar data was collected. The one minute wind data is sampled every 15 minutes so as to mirror the time increment that is used in the analysis by the other forms of generation and storage in the system. The wind power curve for the 3.5 kW wind turbine generator is presented in Figure 2.6.

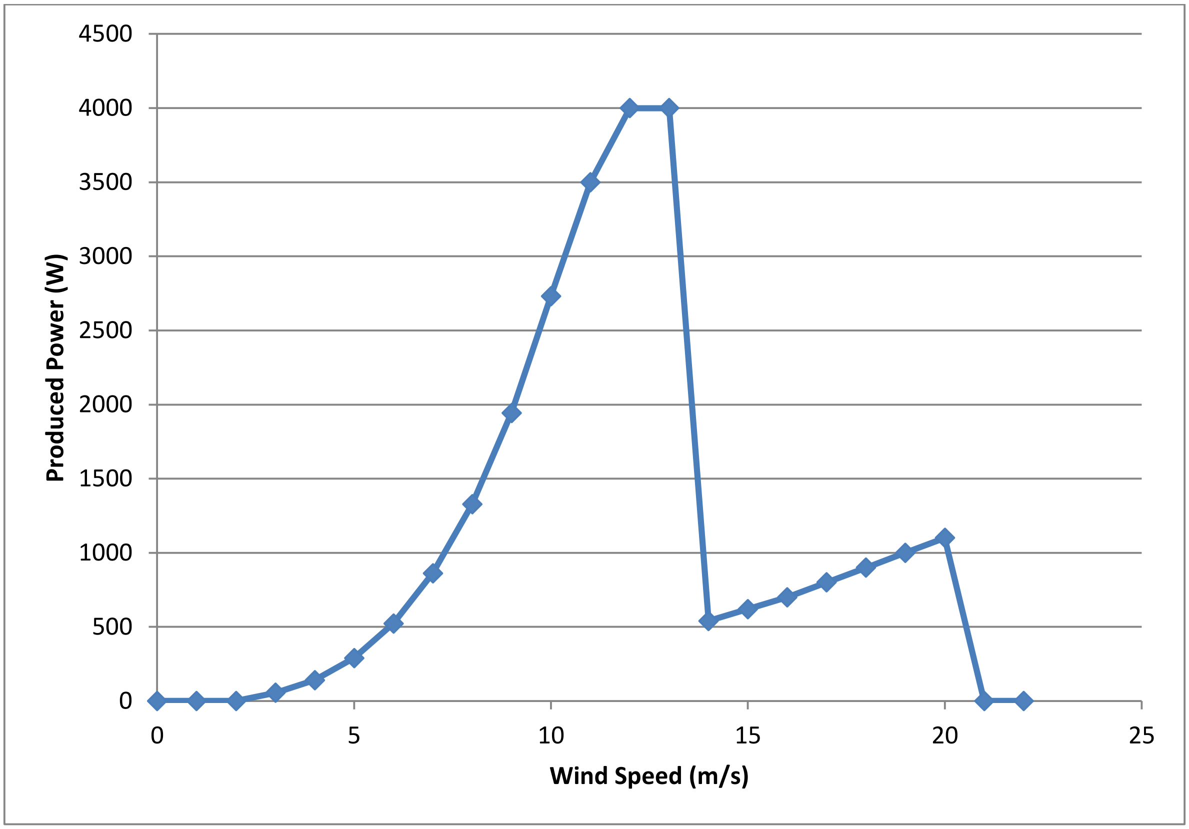

Figure 2.6: Power Curve for Raum 3.5 kW Wind Turbine Generator

The mean annual wind speed measured at the Dalmeny site in 2010 was 4.01 m/s and is comparable to the previous five year average of 4.36 m/s [51] as measured at the Saskatoon Airport approximately 20 km from Dalmeny. Using this data, the annual electrical generation for a Raum 3.5 kW wind turbine is calculated to be 3,030 kWh, and the capacity factor is 9.9%.

The cost of the 3.5 kW Raum turbine is calculated using a quotation received for the purchase of equipment, installation, and foundation work. The total cost of the system is $22,000. This is an equivalent cost of $6,280/kW and is used in estimating the lifetime cost of the microgrid systems. The turbine carries a five year limited warranty, and an estimated 20 year lifetime. The equivalent energy cost based on this lifetime is calculated to be $0.36/kWh.

Note that the pricing in this study is indicative of small-scale wind turbines (with a capacity below 100 kW) and considers the wind profile characteristic of central Saskatchewan. As the scale increases and locations with strong wind regimes are selected, costs can be further reduced.

2.3.3. Fossil Fuel Generation

Fossil fuel generation is commonly used to provide energy to the microgrid when it is disconnected from the utility grid, or the residential load exceeds the system's ability to provide renewable energy.

There are several different types of generators that operate using natural gas, propane, or diesel fuel. Propane is a common fuel used for heating in rural areas where natural gas may be too expensive to install. As of 2015, the cost of liquid propane was approximately $0.72 / L delivered to site in rural Saskatchewan.

For this project, a generator similar to a Generac generator was used for delivering power to the microgrid system. Generac offers residential, commercial, and industrial generators which range in size from 6 kW to 300 kW, and operate on natural gas, propane or diesel. An image of a typical Generac generator is shown in Figure 2.7.

Figure 2.7: Generac Propane Generator [52]

A quotation is supplied by a local company for the procurement and installation of a 17 kW generator with the capacity to use either natural gas or liquid propane as its fuel source. The total cost of the quotation is $8,946.15 which is equivalent to approximately $520/kW.

The liquid propane consumption of this generator is 9.73 L / hour under full load [53], and 6.10 L / hour at 50% load. At the rated generation, the fuel consumption is 0.57 L/kWh, or the energy cost is $0.41/kWh assuming the cost of liquid propane is $0.72/L. In comparison, the fuel consumption at 50% load is 0.72 L/kWh, and the energy cost is $0.52/kWh, which is an increase of 26%.

The integration of energy storage presents the opportunity to implement large amounts of renewable power sources and store excessive energy that can be used during times of low renewable power production. If the levelized cost of energy produced by renewable generation is sufficiently low to legitimize the integration of an energy storage system, the integration of larger amounts of renewable generation could reduce the lifetime operational cost of the resulting system.

There are many different battery chemistries that are readily accessible for mass energy storage. The most predominant of these batteries has been the lead acid battery. It is robust, inexpensive, and well-proven, however, its limited lifetime is a deterrent to its use in this project as the battery may be required to cycle up to two to three times per day. In light of these requirements, the next most well-proven battery chemistry is the lithium-ion battery.

Lithium-ion batteries have recently decreased in price while their characteristics have improved. Companies are now publishing that their batteries are capable of enduring > 8,000 cycles at 80% depth of discharge [54], and they can be continually cycled up to a 90% depth-of-discharge. Also integral to the lithium-ion battery system, a programmable logic controller monitors the state of charge, state of health, rate of charge and discharge, internal temperature, and individual cell energy balance of the batteries to optimize their performance. Lithium-ion batteries are easily scalable to achieve high power and energy ratings. Most large-scale systems are based on the scaling of individual cells much like the cell shown in Figure 2.8.

Prices for lithium-ion batteries vary greatly and depend on the application, size, and requirement for power electronics such as inverters. Costing information gathered for this project shows cost variations ranging from $420/kWh to $2,000/kWh. An article stated that lithium ion batteries are generally found to be between $500 and $1,000/kWh, and are forecasted to decrease 50% - 75% over the next five to ten years [56].

For the purposes of this project, it is assumed that a lithium-ion battery complete with PLC-based inverter costs $750/kWh. The battery also has the ability to achieve 90% depth-of-discharge, and a round trip efficiency of 90%.

Figure 2.8: Saft Medium Power Lithium-ion Cell [55]

2.4. Summary

Section 2 characterizes the load that is used in the microgrid analysis as a small, 5-home microgrid with a peak load of 25 kW and an average energy consumption of 13,807 kWh per home, or a total consumption of 69,035 kWh per annum. The power generation sources that are considered for the microgrid system are photovoltaics, wind turbines, and propane generators. Costing for each of these options is presented. The energy storage component of the microgrid consists of lithium-ion batteries and the battery characteristics including SOC operating levels, lifetime, and cost is also presented.

3. BASE CASE AND OPTIMIZED BASE CASE MICROGRIDS

3.1. Introduction

This chapter assesses the operational cost of the base case microgrid as well as the optimized base case microgrid. The base case microgrid consists of the loads as characterized in Chapter 2, with energy generation provided by propane generation only. This establishes the standard cost of operating a microgrid system with no load control or curtailment, and no renewable generation sources or energy storage.

After the cost and characteristics of the base case microgrid are determined, the microgrid is optimized by integrating renewable energy generation, and energy storage. A MATLAB model is developed to determine the ideal combination of renewable energies and energy storage. The resultant ideal combination is based on the proposed system with the lowest operational cost. This optimized base case is contrasted with the proposed microgrid operated by the smart microgrid management system and is presented in the next chapter.

3.2. Base Case Microgrid

The base case system consists of two 25 kW propane generators installed to serve the 5-home community load. The generation system meets the “N-1” reliability requirement, which means the peak system load is still met with the outage of a generator unit. Although fuel prices for remote communities can be three times the typical costs, it is assumed that delivery of propane to a remote community (such as within Saskatchewan) is \$0.72 / L, as previously stated.

A MATLAB program is developed to determine the fuel consumption of the propane generation as a function of the power requirement of the 5-home community. The evaluation is done using a sequential simulation in 15-minute time increments. The total fuel consumption of the base case system over a 20 year period is calculated to be 771,551 L considering a total annual energy requirement of 69,035 kWh at varying system loads up to 25 kW. The model utilizes the fuel consumption information for the propane generator according to its fuel efficiency, and linearly extrapolates the fuel consumption at loads occurring between given data points. The total capital and operation cost over the 20 year period is $581,517.

3.3. Operation Methodology for Optimized Base Case

Studies show that renewable generation is capable of producing electricity at a cost less than conventional generators on a microgrid scale [57]. Depending on the cost of energy storage, there is opportunity to size the renewable energy capacity such that excess energy generated at the site can be stored via energy storage technologies, thereby further decreasing the fuel consumed by the fossil fuel generators.

Renewable energy generation and energy storage are integrated into the base case system, and the optimal mix of the different generation sources are determined in order to obtain the optimized base case. The optimized microgrid consists of an optimal combination of PV and wind turbine generation, as well as battery energy storage. The microgrid retains the standard generation scheme of two 25 kW propane generators each capable of handling the annual peak load of the community.

The methodology of the optimization model is as follows. During periods when renewable power is available, it will serve the load. If the renewable generation is not sufficient to meet the microgrid load, battery energy is dispatched as needed down to 10% state-of-charge (SOC). If the available renewable generation is greater than the microgrid load, the battery is charged up to 100% SOC. Lastly, if the renewable generation and the available battery capacity is not sufficient to meet the microgrid load, the propane generator ramps up accordingly to meet the generation requirement. The round trip efficiency of the battery is considered to be 90%.

The determination of an optimized base case is financially driven and considers the capital cost of the equipment and the continuing fuel cost for a 20-year period. Maintenance costs are not included in this analysis, with the assumption that the maintenance costs are relatively equal and do not significantly alter the comparison between the different options.

An algorithm is developed to analyze numerous combinations of battery energy storage, wind turbine power, and PV generation capacities. Specifically, the algorithm varies combinations of wind turbine and PV generation by 5 kW increments from 0 kW to 200 kW, and of battery energy capacity between 0 kWh and 200 kWh in 5 kWh increments. A total of 64,000 combinations are modelled with the defined annual load profiles. With each combination, a 20-year lifetime cost is calculated based on the specified renewable generation size, battery energy storage, and generator fuel consumption.

Figure 3.1 describes the conceptual layout of the optimized base case microgrid.

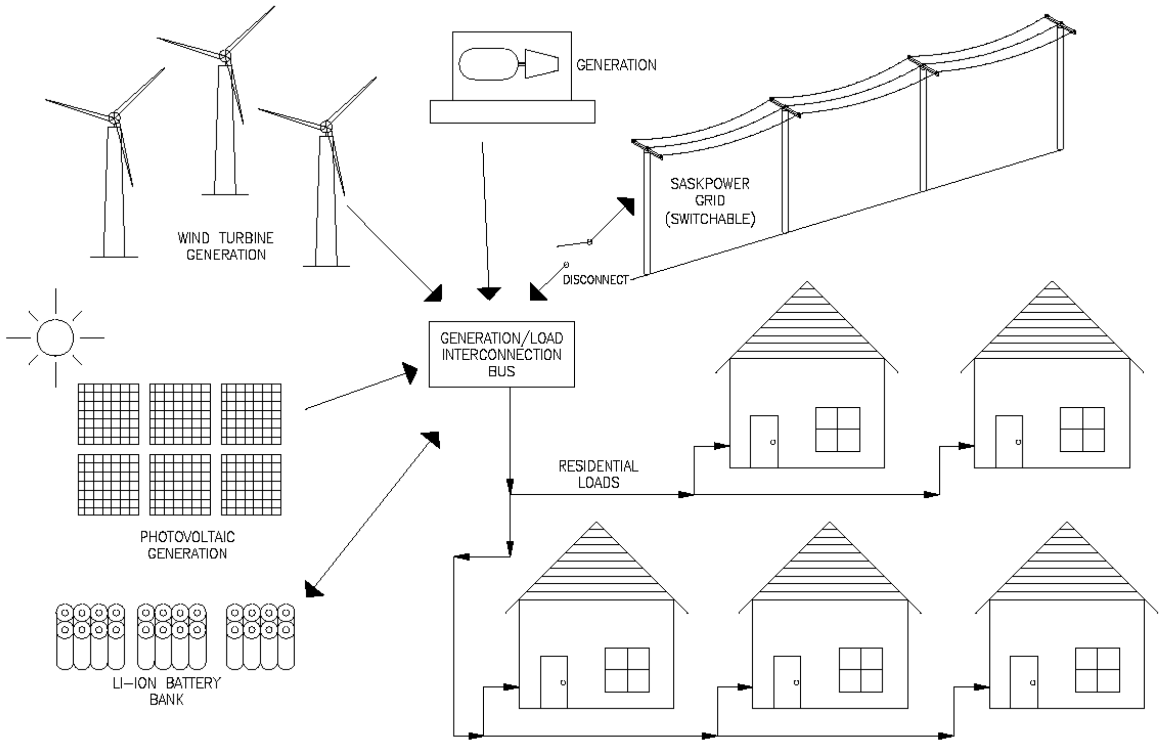

Figure 3.1: Conceptual Optimized Base Case Microgrid Layout

It should be noted that a transfer switch is present in Figure 3.1 as a potential connection to a macrogrid. Although this is a common feature in microgrids, the analysis for the optimized base case and the ideal microgrid with a SMMS as described in the next chapter does not consider that a macrogrid connection is available. For the purposes of this research, the microgrid community is considered to be isolated without a connection to a macrogrid.

Figure 3.2 indicates the proposed control system schematic for the optimized base case microgrid.

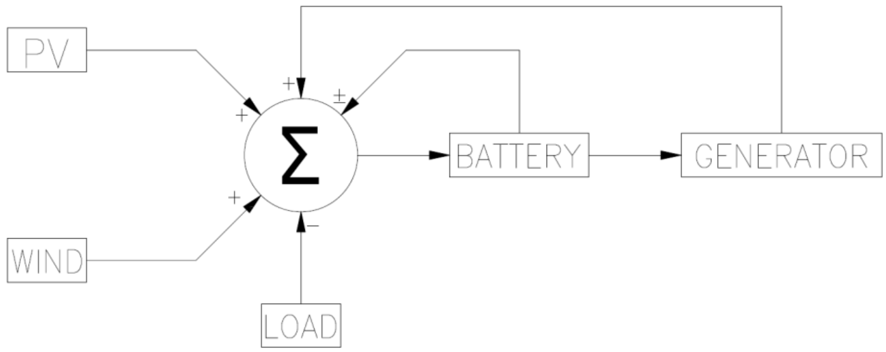

Figure 3.2: Optimized Base Case Control Method Diagram

The optimized base case microgrid contains some flexibility in the way that loads and generation interact when battery energy storage is contained in the system. At any given time, the summation of the load and generation must be equal to avoid power quality issues and service interruption. The battery can supply energy in times of excess load, and absorb energy in times of excess generation, but only for a limited time. Once the battery is unable to meet the system's request to balance the load and generation, the propane generator is started or shut down as required for the balance. If the total generation capacity including the battery storage fails to meet the system load, the load is curtailed. This results in a loss of load event.

3.4. Optimized Base Case

It is determined early in the analysis that there was little benefit in the addition of wind turbine generation. With the cost of small wind power generation being $6,280/kW, there was not enough financial advantage to including it in the renewable generation portfolio compared to the photovoltaic generation which was priced at $4,170/kW. It was anticipated that the photovoltaics' generation being limited to daylight hours may be a detriment to the system at some point, whereas the ability to produce renewable energy at night with wind turbine generation may be a benefit to the wind generation system. However, the fuel costs associated with night-time generation are low enough to negate the limited benefit of wind turbine generation. Wind generation is still assessed in various degrees of penetration in the microgrid for each analysis, however, in each scenario it is always more financially viable to exclude it from the generation portfolio. Furthermore, remote communities in Canada are predominantly located in the north, and a combination of cold temperatures and wind-driven snow and ice are often detrimental to the operation of mechanical systems such as wind turbines, especially small-scale wind turbines which may have not yet reached maturity in Canada.

It is important to note that this analysis of wind turbine generation is not indicative of the larger wind industry. Large wind turbines (> 200 kW) are largely well-proven, reliable, and cost-effective. Only recently have small wind turbines (< 50 kW) experienced a resurgence in Saskatchewan, and the limited economies of scale and experience have not been sufficient to make them a cost-effective method of generation in this analysis.

Depending on the generation and storage combination, the propane generator must operate for a specific amount of time to ensure the load is met. The fuel cost associated with its operation is one of the major components of lifetime cost to the microgrid. Table 3.1 displays a portion of the calculated microgrid lifetime costs associated with varying amounts of battery energy storage, photovoltaic generation, and associated propane generation costs. All costs are based on the previously mentioned costing information.

Table 3.1: Lifetime Costs for Microgrid Combinations

		Photovoltaic Generation Capacity Rating (kW)								
		0	5	10	15	20	25	30	35	40
Energy Storage Capacity (kWh)	0	$581,517	$546,662	$520,106	$509,734	$510,358	$517,201	$527,690	$540,537	$554,963
	10	$589,000	$554,115	$522,421	$505,379	$502,672	$507,696	$516,921	$529,177	$543,315
	20	$596,484	$561,615	$528,531	$505,310	$497,474	$499,409	$507,206	$518,301	$531,568
	30	$603,945	$569,115	$535,956	$508,463	$494,652	$493,032	$498,575	$508,421	$520,971
	40	$611,427	$576,615	$543,456	$513,757	$494,351	$488,685	$491,525	$499,635	$510,961
	50	$618,902	$584,115	$550,956	$520,299	$496,716	$485,691	$485,784	$491,834	$501,912
	60	$626,377	$591,615	$558,456	$527,685	$500,890	$484,794	$481,498	$485,488	$493,667
	70	$633,852	$599,115	$565,956	$535,185	$506,521	$486,410	$478,648	$480,446	$487,194
	80	$641,327	$606,615	$573,456	$542,685	$513,000	$489,842	$477,545	$477,024	$482,275
	90	$648,808	$614,115	$580,956	$550,185	$520,125	$495,093	$479,086	$475,366	$479,314
	100	$656,271	$621,615	$588,456	$557,685	$527,511	$501,349	$482,772	$475,872	$478,429

It can be seen that the optimal lifetime cost of the system occurs when the microgrid system consists of 35 kW of photovoltaic generation and 90 kWh of battery energy storage. For greater amounts of photovoltaic generation there are diminishing returns as the increase in solar production cannot be adequately contained for sufficient periods of time in the battery energy storage system. Likewise, if the size of the battery storage system is increased, the added storage is not be utilized often enough to justify the additional expenditure.

It should be noted that when the microgrid has 0 kWh of storage, and 0 kW of photovoltaic generation, the lifetime cost is $581,517 and represents the base case microgrid operating solely on propane generators. This lifetime cost is 22% greater than the optimized case with energy storage and a PV array. Thus, there is a clear financial benefit for the addition of renewables and storage for a remote community that is dependent on fossil fuel generation.

This optimized combination of generation and storage (35 kW of photovoltaic generation and 90 kWh of battery energy storage) is now considered as the optimized base case to determine the degree of benefit in adding a smart microgrid management system to the microgrid.

3.5. Summary

The capital and operational cost of meeting the community's load solely with propane generators is calculated to be $581,517. The costs and characteristics of various generation sources and energy storage that are considered in determining the ideal microgrid base case is discussed, and an ideal combination of generation sources and storage is presented. This combination is considered the optimized base case system going forward and is compared to the microgrid managed by a Smart Microgrid Management System. The resulting optimized base case consists of a 35 kW photovoltaic array with 90 kWh of storage and two 25 kW propane generators. The lifetime cost of the optimized base case is 18% less than the lifetime cost of the microgrid when operating only using propane generators.

4. Smart Microgrid Management System Development

4.1. Introduction

The chief objective of this research project is to develop a conceptual Smart Microgrid Management System (SMMS) that is able to monitor aspects of generation and load within a microgrid and reduce its lifetime cost while maintaining an acceptable level of reliability. Based on the feedback received from the monitoring system, the SMMS makes decisions to curtail, charge, or discharge available resources with the overall goal of reducing the cost of the microgrid with various portfolios of generation and storage.

This section outlines the development of the SMMS. The methodology of the SMMS is presented in Section 4.2. Opportunities for in-home thermal energy storage are identified and characterized in Section 4.3. An algorithm is developed based on decision-making criteria, and is outlined in Section 4.4. Section 4.5 outlines a conceptual design for the implementation of the developed SMMS and estimated production costs. Aspects that are pivotal to the effectiveness of the control system are ease of implementation, reproducibility, and cost-effectiveness. Combinations of wind and solar generation, and battery and thermal energy storage are modelled to determine the most effective combination of generation and storage that reduces the cost of the microgrid managed by the SMMS over a 20 year lifetime. Results for the modelled combinations are presented in Section 4.6. Section 4.7 compares the benefits of the microgrid operated by the SMMS versus a microgrid only utilizing battery energy storage, and Section 4.7 summarizes the findings of this chapter.

4.2. Methodology

A smart control system is a closed-loop algorithm that operates autonomously to achieve a specified outcome, as indicated below in Figure 4.1. For the purpose of this project, a smart control system is employed to manage the generation components of a microgrid system. It is also used to manage arbitrage, load shedding, and load deferral. The intent is to create a viable business case for the inclusion of a smart microgrid management system for a microgrid

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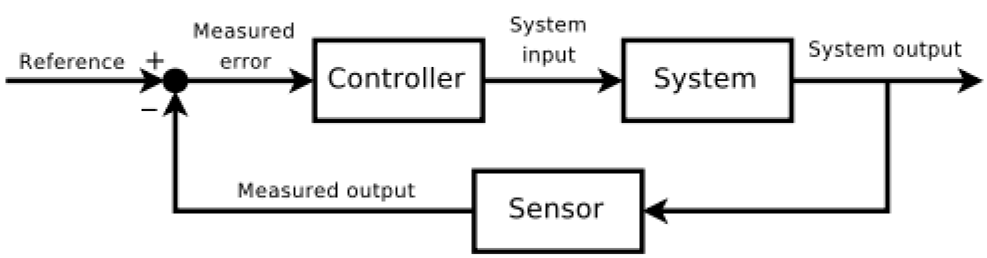

Figure 4.1: Typical Closed-Loop System [58]

Additional control is added to the SMMS to automate disconnection of unnecessary electrical loads in the homes. These loads could include curtailable loads from televisions, microwaves, electric stoves, washing and drying machines, and lighting. In the electrical code, all the aforementioned appliances except lighting and televisions must have dedicated circuits, thus using a smart control system to manage these systems would not be complicated, expensive, or have detrimental effects on other components which could share the same circuit breaker. As well, the implementation of smart circuit breakers in a home to control loads would be a simple and cost-effective retrofit to apply. For this study, load curtailment is limited to exterior lighting loads which are characteristic of the home being modeled and could be controlled during times when their use is not beneficial. Phantom loads are not considered in this model.

The developed SMMS utilizes feedback from in-home residential loads to determine the available amount of storage, and capacity for load shedding and load deferral that is used to transfer energy consumption from times when energy prices are high (such as when the propane generator is running) to time when renewables are able to operate the load.

It was initially presumed that the success of the intelligent algorithm would be limited to isolated microgrids dependent on propane or diesel generation, however, it was soon determined that there could be potential for the successful implementation of an SMMS in any market with a price differential for electricity. Although this price differential tends to be greater in isolated microgrids where solar energy production costs are much less expensive than diesel or propane energy production costs, the SMMS could be implemented for grid-connected homes with an electrical pricing differential between on-peak and off-peak times. If the benefits of the SMMS are sufficient to legitimize its incorporation into a home with a time-of-day electricity pricing market, the potential market would be quite large.

Figure 4.2 depicts the proposed conceptual layout for the SMMS and the associated control method diagram. In this case, both generation and load are connected to a generation / load interconnection bus which is the point of common coupling. There is also a load controller which monitors in-home loads and interacts with the interconnection bus to control electrical generation and storage devices based on desired operating conditions.

The conceptual layout of the SMMS is essentially the same as the optimized base case microgrid, but has the added components of the load controller and its associated bidirectional communication lines which enable smart controls and feedback loops.

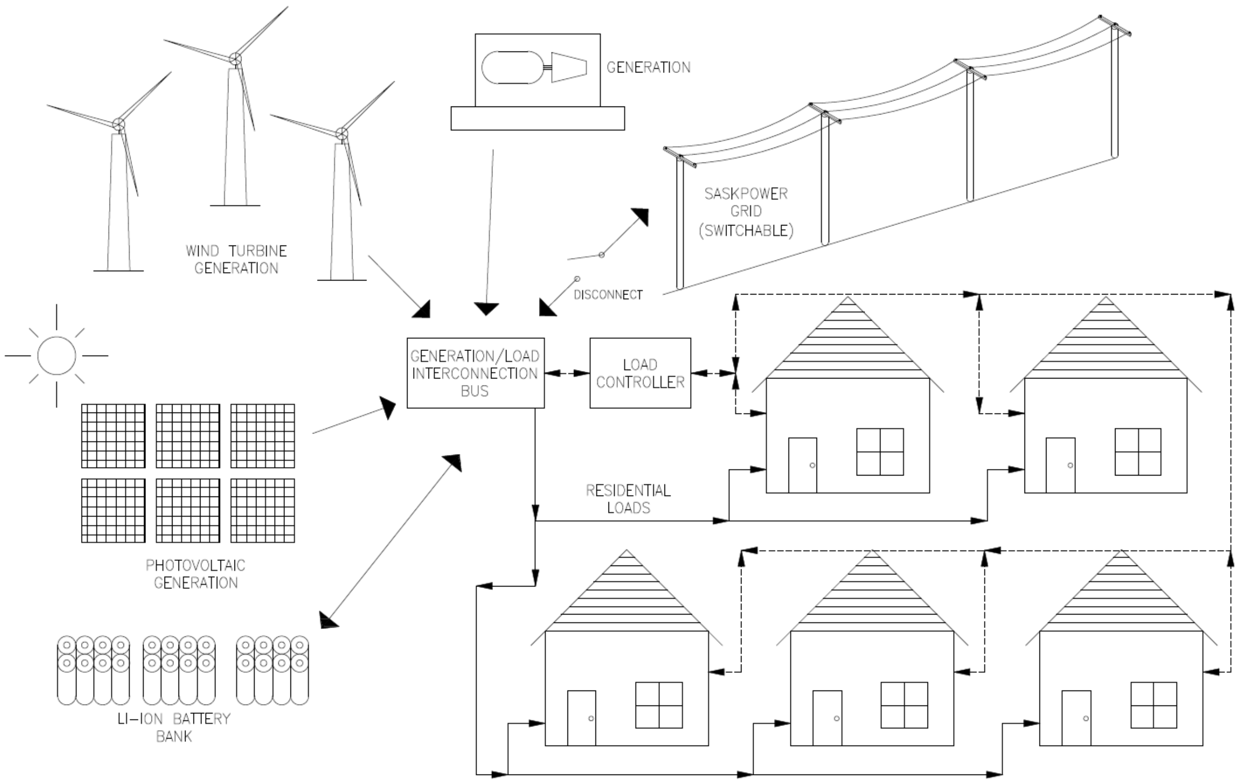

Figure 4.2: Smart Microgrid Management System Conceptual Layout

Figure 4.3 indicates the operating method of the SMMS along with operating priorities. The operating procedure of the microgrid is polled by the SMMS, which analyzes the components of the proposed case, and then determines if there is opportunity for decreasing energy consumption if the proposed case yields a high electricity price. If the SMMS determines that the microgrid is operating at a high electricity rate, the SMMS' first priority is to alter the load to lower the required electrical consumption. Load alteration is achieved via both load curtailment of curtailable loads, as well as load shifting. Load shifting methods are explained later in this chapter. If the cost of operating the microgrid is still considered high, the second priority of the SMMS is to dispatch electrical energy storage from the battery. If the resultant combination is still not capable of meeting the firm community load, the SMMS signals the generator to come online and support the system. In the event that the generator is not operating at full capacity, excess capacity is used to recharge both electrical and thermal energy storage devices.

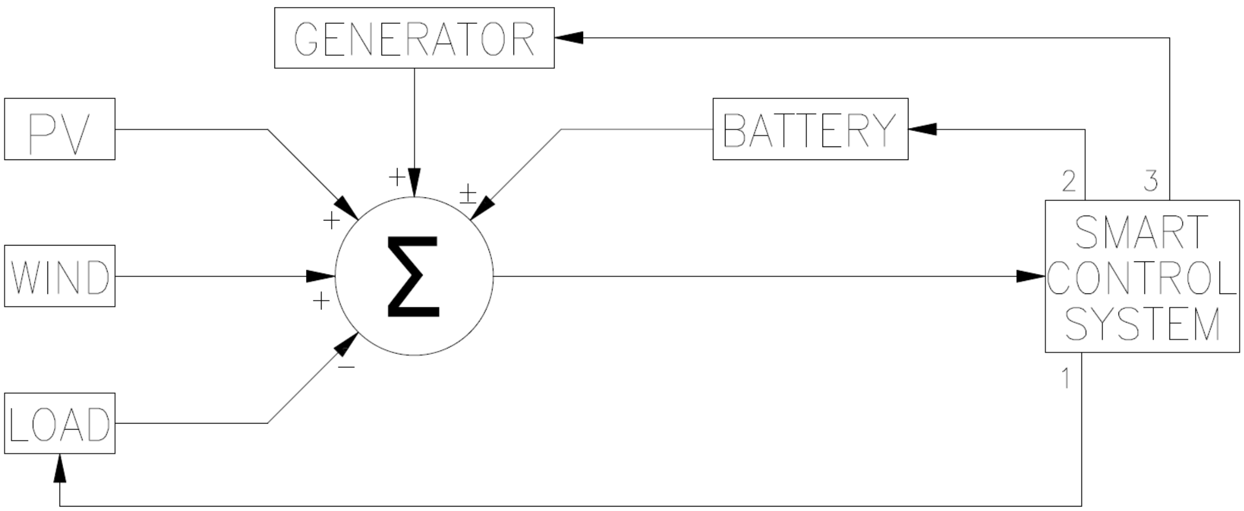

Figure 4.3: Smart Microgrid Management System Control Method Diagram

The reasoning and description of this layout is expounded fully in the following section which discusses the implementation method and associated costs with the development of the SMMS.

4.3. Additional Storage Specifications and Load Shedding

It is recognized that besides battery energy storage, additional opportunities exist within residential homes to provide other forms of energy storage and load shedding that can be used by the SMMS to execute DSM techniques to defer part of the microgrid's load for a given time when it proves to be more financially beneficial.

Curtailable Load Shedding (CLS) is simply the curtailment of specific loads. Within the scope of this project, it is not the intention to curtail important loads that would inconvenience the residents of the community, thus, only exterior lighting will be considered for CLS control. CLS of the exterior lighting will only occur during times when exterior lighting is not likely utilized, such as between the hours of 12:00 AM and 6:00 AM daily. Exterior lighting loads indicative of the model home consists of three 60 watt soffit lights, and one 175 watt mercury vapor yard light.

Another opportunity to further increase the financial viability and flexibility of the microgrid using the SMMS is identified through the ability to manage in-home thermal storage. Every residence contains components which have thermal mass which can be used for thermal storage. These storage components include domestic hot water heaters, freezers, refrigerators, and even the home's air, walls, and floor. For the purpose of this project, the thermal storage mediums of an electric domestic hot water heater and a geothermal mass tank are considered – both indicative of the home after which the system is being modelled.

A 50 US gallon, two-element electric hot water heater has a rating of 4.5 kW and is indicative of a typical residential electric hot water heater. The temperature of a hot water heater is crucial to safety, and must be regulated between specific temperatures so as to decrease the probability of contracting legionella pneumophilia pneumonia (also known as Legionnaires Disease) which can be caused by domestic hot water temperatures below 49°C, as well as to reduce the risk of tap water scalds which can be caused by temperatures above 60°C [59]. Thus, the allowable temperature variation in the hot water heater is between these two limits. The available energy storage in the hot water tank is calculated as shown in Equation (4.1).

$$\Delta Q = \frac{m c_p \Delta T}{3{,}600} \qquad (4.1)$$

where,

ΔQ = change in energy (kWh)

m = mass of water (189.27 kg)

c_p = specific heat of water (4.18 J/g°K)

ΔT = temperature differential (11°C)

The resultant energy storage available for smart control in the intelligent system is 2.42 kWh per home, or a total of 12.1 kWh for the five-home system. The associated duty cycle of the hot water heater is approximately 12.5%, based on measurements taken from the model home's energy monitoring system. This duty cycle agrees with other reference material indicating the average duty cycle of electric hot water heaters [60]. With a 12.5% duty cycle, and a power rating of 4.5 kW per home, this means that at any given time, the average power available both for hot water heater charging and discharging in the five-home network is given by Equation (4.2).

$$P_{avg\ HWH} = (P_{max})(D)(x) = 2.8125\ kW \qquad (4.2)$$

where,

$P_{\text{avg HWH}}$ = average power available for DSM in the smart microgrid

P_{max} = maximum power draw of a single electric hot water heater

D = duty cycle

x = number of homes

Thus, an average of 2.81 kW is available within the microgrid for charging and discharging which raises and lower the temperature of the hot water respectively. The model uses this average hot water heater power to charge and discharge the domestic hot water energy storage system within the microgrid. To simplify the methodology, this domestic hot water energy storage system is modeled as a battery energy storage system with a total energy storage capacity of 12.1 kWh.

If the proposed ideal microgrid system were to be implemented in the field, this method of tracking the current energy of the hot water heater would be replaced by a feedback system which would send information regarding the current temperature and power consumption for the entire hot water heater array to the SMMS via a residential controller and internet connection.

The ground source heat pump (GSHP) heating system characteristic of the group of homes being analyzed is a 3-ton in-floor heat pump with a rating of 4.5 kW. It delivers heat to a 50% ethylene glycol – water mixture which is stored in a 50 US gallon insulated mass tank. This system is controlled by an integrated aquastat which monitors the temperature of the mass tank, and signals the in-floor heat pump to deliver more energy when needed. The available temperature differential allowed in the mass tank is 10°C. It is understood that when the temperature of the mass tank is decreased, in-floor loop pumps must be run longer to deliver the same amount of heat to the loop, however, when the mass tank temperature is higher than normal, these pumps will run at a reduced time. Thus, it is assumed that the net energy consumption due to varying the temperature set point is neutral as long as the model continues to cycle the system.

The available energy storage in each mass tank is calculated using Equation (4.1) where,

ΔQ = allowable variation in energy storage (kWh)

m = mass of 50% ethylene glycol - water mixture (205.93 kg)

c_p = specific heat of 50% glycol-water mixture (3.41 J/g°K)

ΔT = temperature differential (10°C)

The resulting available energy for storage is 1.95 kWh/home. It is also calculated, based on measured energy consumption in the model home, that the duty cycle of the heat pump system is 8.9%. This equates to a cumulative energy differential of 9.75 kWh for a five-home network. This means that the average power available for geothermal mass tank load shedding in a five home system is given by Equation (4.3).

$$P_{avg\ GSHP} = (P_{max})(D)(x) \qquad (4.3)$$

where,

$P_{avg\ GSHP}$ = average power available for DSM from the ground source heat pump

P_{max} = maximum power draw of a single ground source heat pump (4.5 kW)

D = ground source heat pump duty cycle (8.9%)

x = number of homes (5)

Thus, the average GSHP power available for deferral for the 5-home microgrid is 2.0 kW based on the equation above. Much like the case for the electric hot water heaters, this GSHP array is modelled as a 2.0 kW battery with a total energy storage capacity of 9.75 kWh.

Other potential methods of utilizing thermal energy storage that are not explored in this project include the use of freezers, air conditioners, ambient air heating and cooling, and purposefully installed thermal energy storage such as bricks, concrete, or water tanks. Figure 4.4 shows the components of residential homes that are considered for this project, as well as some of the additional potential components that could be used for further thermal storage.

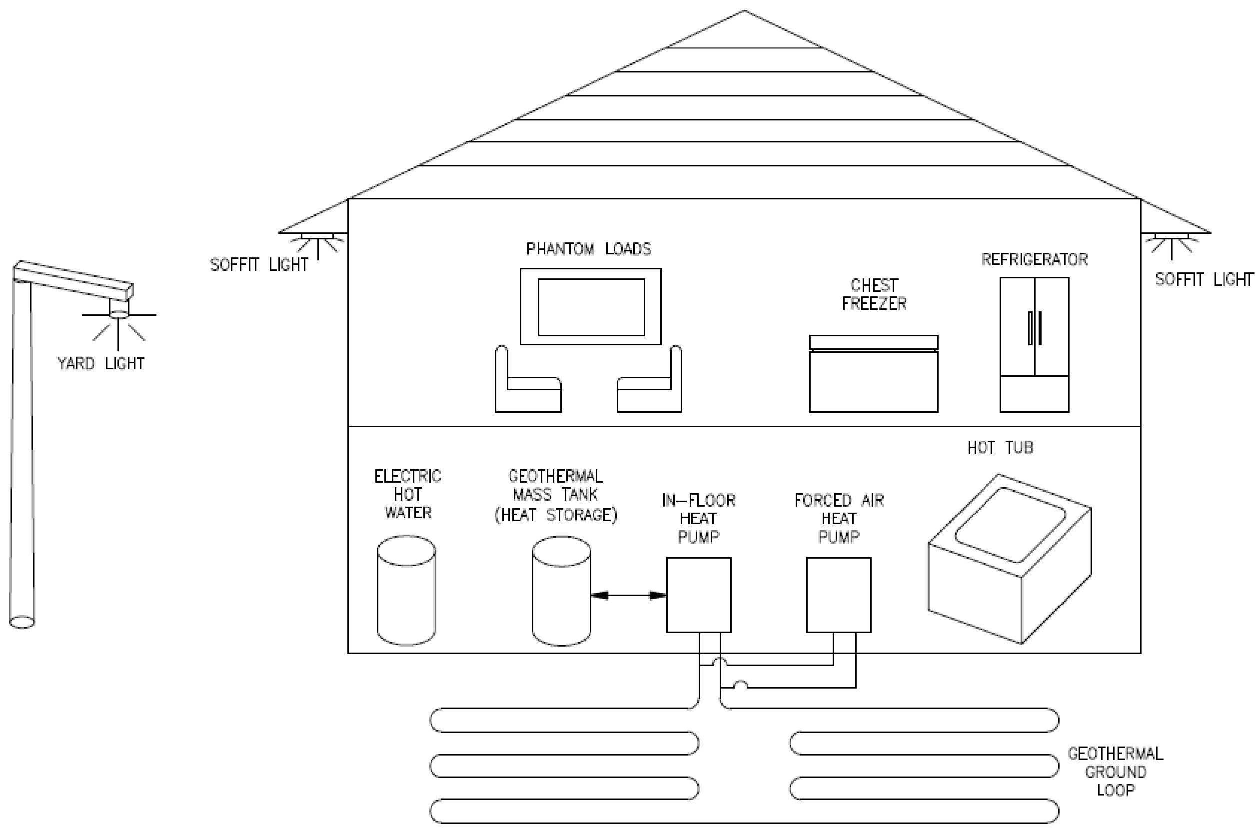

Figure 4.4: Components Available for Smart Management

4.4.	Algorithm Development

The SMMS operates in a closed-loop feedback system that monitors the instantaneous power generation of its renewable components, the real-time load consumption of the homes in the system, the available thermal mass and ability to defer and shed load, and the state of charge of the lithium-ion battery bank.

The decision-making flow chart is shown in Figure 4.5, an explained below.

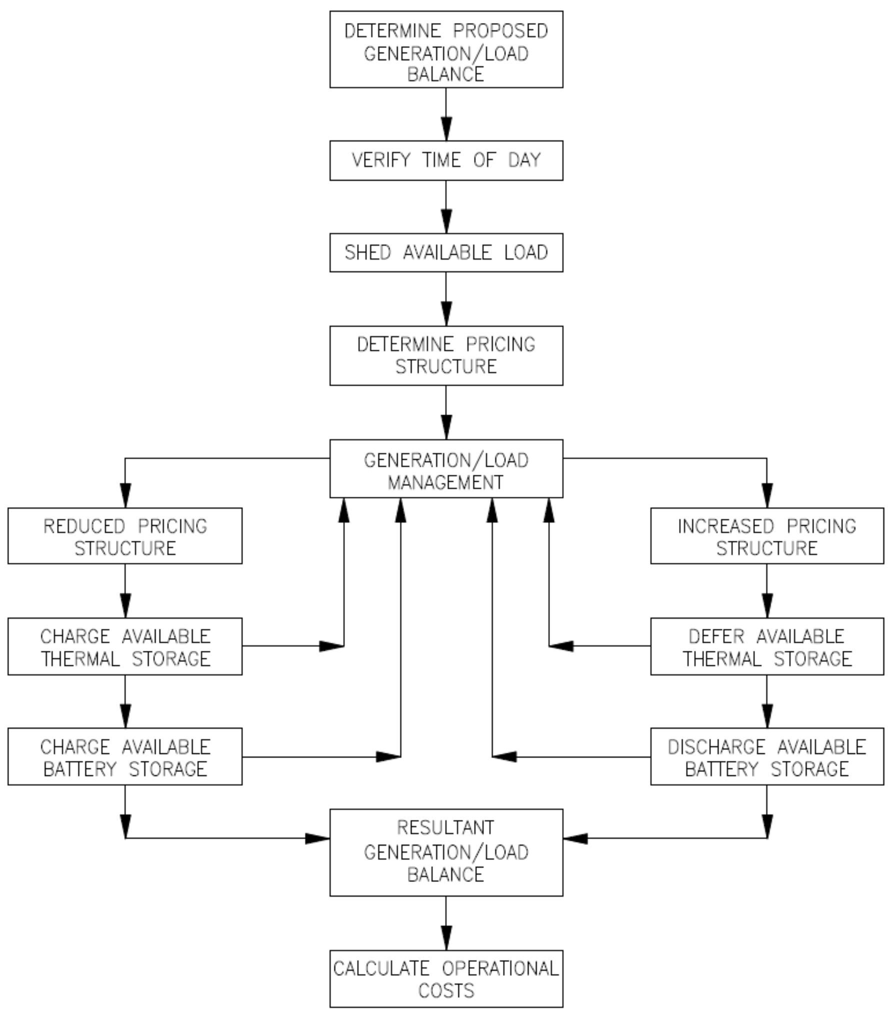

Figure 4.5: Smart Control Algorithm Flow Chart

The first function of the smart microgrid management system is to determine the current generation capabilities and characteristics of the available renewable generation, battery storage, and propane generation sources. This information is contrasted with the current call for load from the homes in the network, and determines the potential net balance of the system.

The second function of the algorithm is to determine the time of day. The time of day dictates which loads can be turned off. Time-of-day verification would also be required if a similar system were implemented for a grid connected microgrid which has time-of-day electricity pricing which will be discussed later.

The next decision step in the algorithm pertains to shedding available curtailable loads within the microgrid. Regardless of the pricing structure, loads which can be curtailed are the most viable methods of reducing energy consumption and its associated cost. Although the model can be altered, it is assumed that external lighting such as yard lights are curtailed between the times of 12:00 AM and 6:00 AM.

The cost of electrical generation is defined in the 'Determine Pricing Structure' step. This could be simply determining the current time-of-day electricity price in a grid-connected electricity market, or in the case of this project, this entails analyzing renewable and non-renewable generation constituents with a weighting or priority as to which methods produce electricity at discounted rates. For grid-connected time-of-day electricity markets, there are firm time limits to distinguish on-peak, mid-peak, and off-peak pricing schemes. The SMMS would use the site-specific pricing scheme to control loads and storage with the overall goal of reducing the cost of operation in these markets. It is important to note that all microgrids, irrelevant of whether or not they are connected to a macrogrid, are subject to tiered electricity pricing. For instance, if multiple generation technologies exist, they will each have different costs of electricity generation, and the

SMMS can determine how to operate the microgrid most efficiently. As well, even if a microgrid is operating only with a single fossil fuel generator, depending on the loading of the generator, electricity will be produced at varying rates due to the generator's efficiency at different loads.

The output of the 'Determine Pricing Structure' step provides the 'Generation / Load Management' step with information regarding whether energy costs are high (such as when the generator is supplying energy) thereby implementing energy conservation and/or energy deferral, or whether energy costs are low and available energy storage devices can be charged.

The 'Generation / Load Management' task assesses the feedback received from thermal management storage devices in the form of current temperature, energy consumption, and availability and determines the system's capability to store or defer energy. For the purposes of this project, this entails monitoring the domestic hot water heater and the geothermal mass tank to determine if there is any latitude in raising or lowering temperatures that can create financial benefit for the system. A subsequent decision is made according to received feedback from the pricing structure and available energy storage as to whether the system should pursue load deferral or charge thermal loads. Based on the decision from the 'Generation / Load Management' process, the thermal energy storage systems are instructed to either increase their temperature to absorb energy and recharge during times of discounted electricity, or are turned off to conserve energy until they reach a lower limit or electricity prices decrease again. The rate at which they are expected to charge or defer energy is dictated by the duty cycle and power rating of the technology as described in Section 4.3.

Depending on the system's capability to absorb energy imbalances through curtailable load shedding, or thermal charging and deferral, the battery charges or discharges accordingly to meet the system's remaining requirements within the battery's specified limits.

Lastly, if a negative energy balance remains after curtailment, energy deferral, and battery discharge measures are implemented, the remaining energy requirement is supplied by the propane generators. Note that in the case of a grid-connected microgrid, the macrogrid would supply the remaining energy assuming that the electricity price is lower than that of the propane generation within the microgrid.

The program performs this decision loop in 15 minute increments for the duration of the specified 20 year period. All equipment characteristics such as charge / discharge limits, and round trip efficiencies are integrated into the algorithm and are subject to the properties set out in this thesis.

4.5. Conceptual Design of Remote Monitoring and Control

In order to accurately gauge the potential for implementation of the proposed SMMS, a review of possible methods of implementation and associated costs is performed.

A concept for the system to manage a microgrid, both on the generation side as well as the load side, is presented in the following section. Key highlights include:

- System integrates with existing technologies to avoid development overlap
- Scalable design allows for the monitoring and control of variable amounts of residential loads
- Intelligent algorithm is located at central server, and allows for the use of research tools such as MATLAB
- Central server is capable of controlling a large number of subsystems with negligible cost increments

- Remote access to system settings simplifies installation, diagnostics, and testing as well as allows for preferential remote management and manual override

Figure 4.6 shows the conceptual layout of the remote monitoring and control system that is required to facilitate the proposed SMMS. Main components of the design include the generation site with associated interfaces, a server site which facilitates the algorithm and relevant lookup tables that govern site characteristics, and a residence with feedback sensors and controllable loads. Each of these components are interconnected to a local network or the internet to allow for a flexible, plug-and-play SMMS.

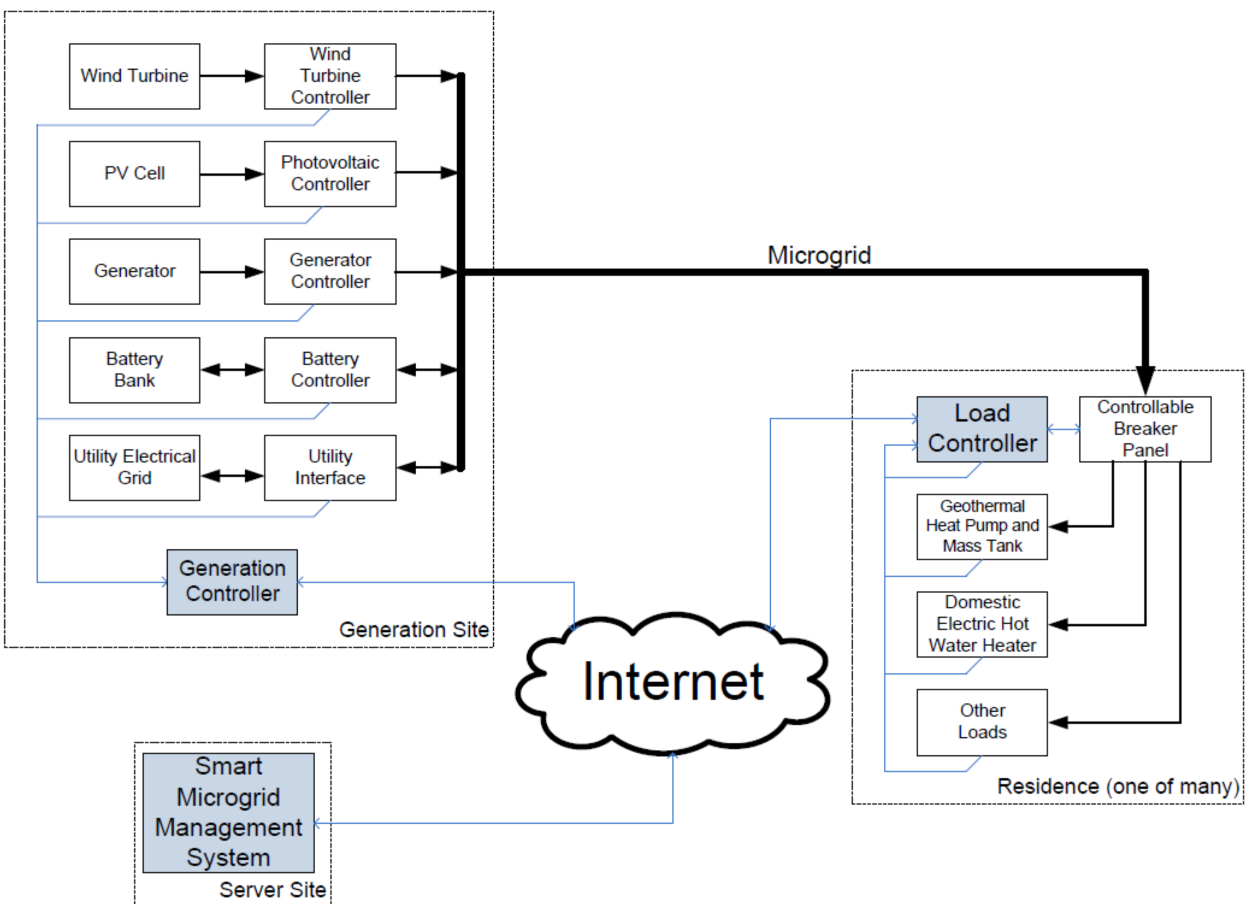

Figure 4.6: Microgrid Control System

The Generation Site includes all electrical generation and storage devices. It is assumed that all devices are designed to connect to a common electrical point, and the original equipment manufacturer (OEM) controller can be interfaced to a system controller such as a programmable logic controller (PLC) which is labeled as the Generation Controller.

The Generation Controller provides an interface between the physical devices (Wind Turbine Controller, Photovoltaic Controller, etc.) and the SMMS. Physical connections to the generation controllers vary by manufacturer and can range from analog and digital inputs and outputs, to standard protocol bus communications such as MODBUS and DeviceNet. Connection to the SMMS is via a persistent internet connection. The Generation Controller is programmed to constantly read and hold information from the generation interfaces, and to supply this data to the SMMS upon request. The Generation Controller is also programmed to set outputs in response to commands from the SMMS (e.g. disconnect grid, set battery controller to charge, turn on ancillary generation, etc). The Generation Controller requires hardware and programming specific to the installation, depending on the generation devices that are installed. In the case of a grid-connected microgrid, the generation controller would not be required, rather, the pricing structure of the electricity utility would be preprogrammed into the SMMS.

A developer provided the following cost estimates for the development and continuing costs for the Generation Controller:

Development: $15,000

Ongoing Equipment and Assembly (per unit): $1,000

The Residence portion of the conceptual design could be comprised of one or several residences. The residence embodies the point of electrical load. The key components are a Load

Controller, feedback systems, and loads. Loads may provide control system feedback to the Load Controller in the form of current system temperature, power consumption, or other pertinent system characteristics.

A controllable circuit breaker, such as the one shown in Figure 4.7, could also be employed to aid in the shedding and deferral of loads. A controllable panel circuit breaker is very similar to a standard electrical circuit breaker in a distribution panel, with the exception that the breakers are designed to be controlled by some central controller. The breakers may also provide feedback information such as current draw, and can be used to determine the duty cycle of connected components. There are many Controllable Breaker Panels available on the market with prices ranging from $400 and up. This method could be used to turn devices on and off, but may not be necessary depending upon the method of control. As an alternative, relays operated by the Load Controller could curtail certain loads and provide feedback to the SMMS. In the case of electric hot water heaters and ground source heat pump mass tanks, the existing thermostats could be intercepted by the Load Controller, and provide the tank sensor with an altered reading to achieve additional heating, or energy deferral, however, there may be liability issues associated with this method of operation.

Figure 4.7: Solenoid-Operated, Remote-Controlled Eaton Circuit Breaker [61]

The Load Controller is a PLC or microcontroller-based device with connections to the controllable breaker panel and/or curtailment relays, feedback signals from various loads, and the internet (through the home owner's internet service provider). The primary purpose of the Load Controller is to provide an interface between the controllable breaker panel or individual load components and the SMMS. The Load Controller also provides physical connections for the feedback from various loads, as necessary. The Load Controller is primarily a hardware interface that allows control to be handled by the SMMS, requiring little or no programming that is particular to a site. Settings at installation would mostly consist of identifying loads with dedicated feedback inputs. This information is labeled and saved in the SMMS, not in the Load Controller. This flexibility allows for the distribution and implementation of the controller to be more efficient and cost effective. The following costs were supplied by a local developer and encompass the preliminary development and design of the Load Controller, and the subsequent charge on a per unit basis for the parts and assembly of the Load Controller:

Development: $15,000

Ongoing Equipment and Assembly (per unit): $500

The Server Site is the location of the software that houses the microgrid data and executes the SMMS. The SMMS as it pertains to the server site would consist of a set of software services, applications and a database. Specifically, the SMMS could run on a Windows server computer, the software could be written in a standard language such as .Net, and the database could reside on a relational database server such as Microsoft SQL Server.

The overall function of the Server Site is to remotely manage a microgrid (or several microgrids) with an intelligent algorithm. It does this by keeping a current state (feedback) of the physical microgrid in a database using synchronizing processes for both Generation and Load Controllers. The SMMS uses the microgrid feedback database to generate new output settings, which are then fed back to the Generation Controller and Load Controller via the synchronizing processes.

A conceptual diagram identifying the key processes and data structures of the Server Site is shown in Figure 4.8 below.

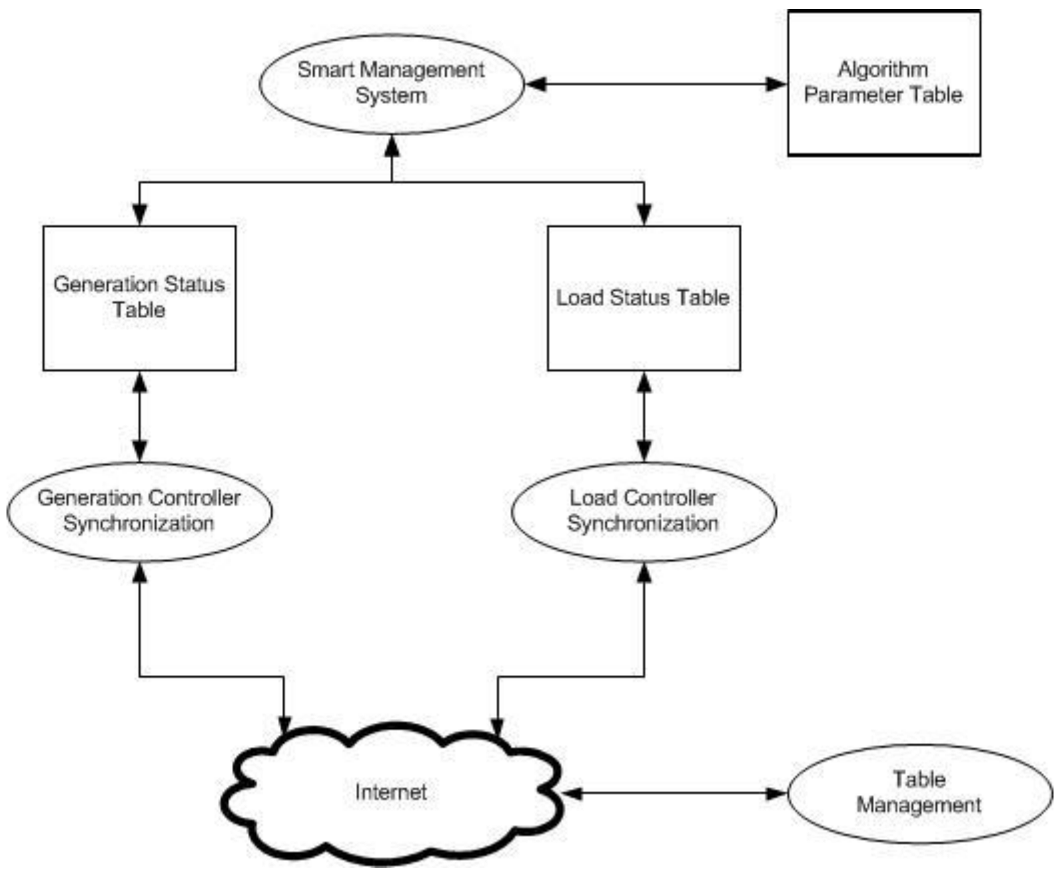

Figure 4.8: Server Site Conceptual Diagram

The Smart Management System is the main process that acquires status data from the Generation Status Table, the Load Status Table, and the Algorithm Parameter Table and sets outputs to determine load deferral, shedding, and charging opportunities. The SMMS will also update the Generation Controller Synchronization Process to determine how generation components are managed. The SMMS could be written in a number of languages, including MATLAB, as long as it is capable of database access.

Generation Controller Synchronization is the process that keeps the Generation Status Table data current with the signals received from the on-site Generation Controller. It is also responsible for polling the output portions of the Generation Status Table and sending the appropriate signals to the on-site Generation Controller to manage the generation characteristics of battery storage and/or ancillary generation.

The Load Controller Synchronization process operates in the same fashion as the Generation Controller Synchronization process. Its purpose is to keep the Load Status Table updated with feedback from the in-house loads for use by the SMMS, as well as polling the Load Status Table to determine functional changes in load strategy that the smart microgrid management system implements.

Table Management is the process that allows a user to manage the data that is in the database. This is necessary for installation, maintenance, troubleshooting, or even a manual override. The Table Management process could range in complexity from a database management tool to a web interface that allows remote set up and testing (such as in the case of setting up a new Load Controller, one could enter information into the database via a browser or mobile application, and could test functionality of the load feedback and load control systems).

Each external generating or storage device would be stored in the Generation Status Table, and it would include all parameters such as power consumption and production, operational time, capacity, enabled state, etc. There are also entries in this table reserved for the control of each generation component.

The Load Status Table stores all the parameters associated with the necessary feedback systems and control outputs for each load system that will be on the control network. In addition, the table also contains information such as owner identification number, manual override, current status, etc.

Parameters for use by the algorithm are stored in the Algorithm Parameter Table and would include the custom generation and load makeup of each microgrid system as well as set points and limits that would be used to control the individual components. Algorithm Parameter Table values could be changed in real-time to reflect operational priority and the possible addition of loads in the microgrid.

The following costs were supplied by a local developer and are indicative of costs associated with the development and implementation of the server site, and ongoing operational costs related to online subscription and storage services:

Development: $35,000

Operational Costs: $50/month

Equipment Capital: $0

4.6. Results

The SMMS MATLAB algorithm analyzes 64,000 combinations of generation and storage options ranging from 0 to 200 kW of each of wind turbine generation and PV generation in 5 kW increments, and 0 to 200 kWh of energy storage in 5 kWh increments. The algorithm also incorporates the proposed methods of curtailable load shedding and load deferral according to the limits that have been established in Section 4.3.

Costs are calculated based on the required capital of the modelled generation and storage portfolio as well as ongoing fuel costs associated with the propane generators. Once again, maintenance and replacement of the propane generators is not considered in the 20-year lifetime costs because this does not represent additional cost compared to the base case microgrid solely reliant on propane generators. The costs of maintenance and replacement are evident in both cases, and do not have to be considered when drawing financial comparisons. Note that the base case microgrid requires the propane generators to operate continuously and at a lower loading compared to the optimized base case or the ideal microgrid operated by the SMMS, and are likely characterized by additional maintenance costs and shorter lifetime that is not been captured in this analysis.

Table 4.1 indicates the calculated 20-year lifetime costs of capital and operation of a microgrid operated by a SMMS which includes control of residential loads, thermal energy storage, and the associated costs to the consumers of the implementation of the SMMS as described in Section 4.5. The costs of the SMMS are included in the 20-year lifetime calculation considering a 5-home community with curtailable lighting and remote load control of both the electric hot water heater and the ground source heat pump mass tank.

Table 4.1: Lifetime Costs of Various Combinations of Microgrids

		Solar Generation (kW)							
		0	5	10	15	20	25	30	35
	0	$549,394	$514,334	$477,043	$447,930	$434,740	$434,443	$440,713	$451,494
	10	$556,871	$521,834	$484,537	$452,130	$433,462	$429,759	$433,830	$443,115
	20	$564,348	$529,334	$492,037	$457,911	$434,359	$425,934	$427,369	$434,913
	30	$571,829	$536,834	$499,537	$464,813	$437,389	$423,914	$422,654	$427,998
	40	$579,302	$544,334	$507,037	$472,274	$442,520	$424,241	$419,616	$423,004
	50	$586,775	$551,834	$514,537	$479,774	$448,739	$427,274	$418,566	$420,087
Battery	60	$594,249	$559,334	$522,037	$487,274	$455,685	$432,223	$419,915	$419,317
Energy	70	$601,725	$566,834	$529,537	$494,774	$462,785	$438,447	$423,684	$420,369
Storage	80	$609,202	$574,334	$537,037	$502,274	$469,978	$445,156	$428,966	$423,286
(kWh)	90	$616,687	$581,834	$544,537	$509,774	$477,274	$452,116	$434,986	$427,886
	100	$624,147	$589,334	$552,037	$517,274	$484,601	$459,126	$441,548	$433,582
	110	$631,628	$596,834	$559,537	$524,774	$491,968	$466,160	$448,295	$440,042
	120	$639,108	$604,334	$567,037	$532,274	$499,409	$473,284	$455,232	$446,746
	130	$646,578	$611,834	$574,537	$539,774	$506,871	$480,468	$462,242	$453,548
	140	$654,048	$619,334	$582,037	$547,274	$514,371	$487,623	$469,357	$460,438
	150	$661,529	$626,834	$589,537	$554,774	$521,871	$494,810	$476,506	$467,448

Table 4.1, above, is reproduced as a 3-dimensional surface plot in Figure 4.9 below to visually indicate the reduction in cost associated with added photovoltaics and energy storage, and the inflection point that occurs when the ideal combination is achieved at a combination of 50 kWh of electrical energy storage and 30 kW of photovoltaic generation.

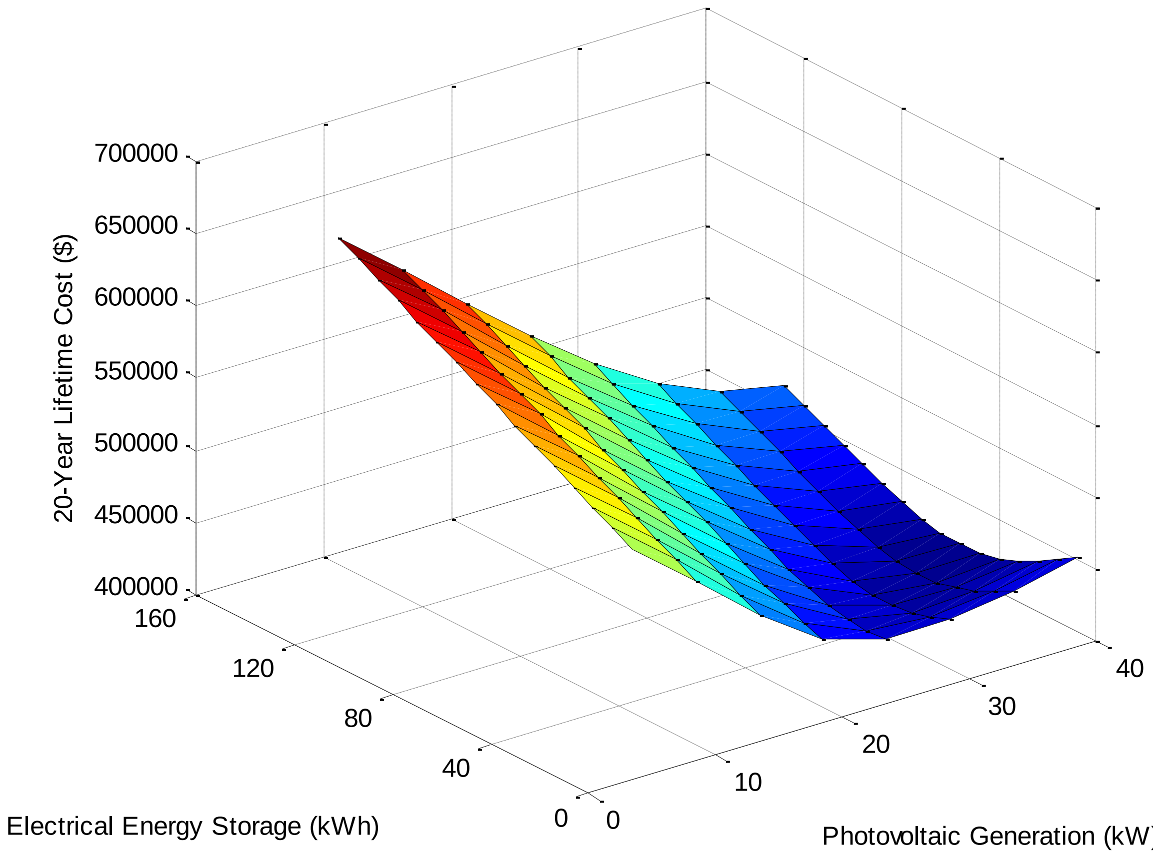

Figure 4.9: 3-D Plot of the Lifetime Costs of Various Microgrid Combinations

The total cost of the ideal microgrid operated by the SMMS utilizing in-home thermal energy storage and load curtailment reduces the 20-year lifetime operational and capital cost of the system from $475,366 with a combination of 35 kW of PV generation and 90 kWh of battery energy storage to only $418,566 with a combination of 30 kW of PV generation and only 50 kWh of battery energy storage. By utilizing in-home thermal storage, the amount of required electrical energy storage decreases, which is intuitive. As well, the required photovoltaic generation decreases as less generation is needed to operate the microgrid due to load curtailment and the ability to shift loads.

4.7. Comparison of Battery Storage Versus the Smart Microgrid Management System

It should be noted that the value of battery energy storage systems may be equal or greater than the value of the SMMS with integrated energy storage. Both systems have initial costs associated with them, but provide continuing economic benefit given an electricity price differential. This section outlines the comparison of these two options to determine if there is adequate additional benefits offered by the SMMS to legitimize its additional cost.

The assessment of these two options used the following assumptions:

- Battery energy storage costs = $750/kWh,
- Smart Load-Management System installation and equipment costs = $500/home,
- The off-peak price is used as a fixed base set at $0.08/kWh, and the energy price differential is determined using a variable on-peak electricity price,
- Both systems contain equal storage capacity and operated in a grid-connected home.

Analysis of the two options reveals that due to the assumed 90% round trip efficiency of the battery energy storage system, the cost differential between high peak and low peak electricity pricing must be greater than 10% for the battery to generate positive revenues. This is contrasted against the same system managed by the SMMS which proves to be financially beneficial even in markets without time-of-day electricity pricing if there are loads that can be shed such as exterior lighting or phantom loads.

As well, the system managed by the SMMS proves to be more cost-effective with a faster payback time in each of the analyzed options as summarized below in Table 4.2.

Table 4.2: Payback Period Associated with Various Energy Price Differentials

	Payback (Years)	
Electricity Price Differential ($)	**Battery**	**Smart Microgrid Management System**
0.00	Infinite	7.1
0.01	2054.8	5.2
0.03	108.1	3.3
0.06	44.7	2.2
0.09	28.1	1.6
0.12	20.5	1.3
0.15	16.2	1.1

Figure 4.10, below, offers a visual representation of the findings. In each of the cases, the system being managed by the SMMS offers a payback in less than 10 years, even in markets with no electricity price differential.

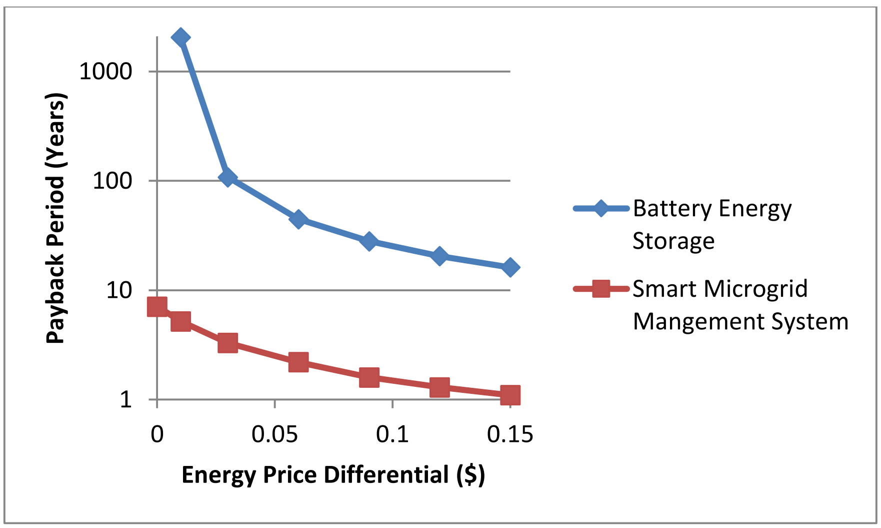

Figure 4.10: Logarithmic Payback Period Comparison

4.8. Summary

The operational methodology for the algorithm is presented. The algorithm operates as a closed-loop feedback system, and the algorithm has the ability to both curtail and defer loads to the financial benefit of the system.

A proposed conceptual layout for the SMMS is presented complete with a generation / load interconnection bus to connect the various sources of generation and electrical storage to the load. A load controller is co-located with the interconnection bus, and communicates between the in-home loads and the server-based controller application to dictate the operation of the generation and energy storage sources. The priorities of the controller are defined in the SMMS Control Method Diagram.

Existing in-home thermal storage and load shedding opportunities are explained and defined. The SMMS utilizes a total of 295 watts of curtailable lighting between the hours of 12:00 AM and 6:00 AM. In addition, thermal storage in the form of domestic hot water heaters and ground source heat pump mass tanks exists in the conceptual homes that enables a total of 2.81 kW / 12.1 kWh, and 2.0 kW / 9.75 kWh respectively. The temperature differential for each of the thermal storage devices is dependent upon safe operating temperatures.

The algorithm flow chart is presented, and consists of a series of decision-making processes that depend on real-time feedback from the loads, thermal storage, electrical storage, and electrical generation systems. The overall purpose of the system is to reduce the operational cost of the microgrid.

A conceptual design for the remote monitoring and control that is necessary for the actual implementation of the system is presented along with proposed functionality, technical highlights, and estimated costs.

The SMMS algorithm is run in the MATLAB environment and analyzes several combinations of electrical generation and electrical storage. The most cost-effective combination of electrical generation and storage occurs with 50 kWh of electrical energy storage, and 30 kW of photovoltaic generation. This represents a reduction in electrical energy storage of approximately 45% versus the ideal microgrid combination when not employing in-home thermal storage or curtailment. As well, there is a 15% reduction in the required amount of photovoltaic generation. The overall lifetime cost of the 5-home microgrid is reduced to $418,566. This represents a reduction of 28% ($162,951) compared to the base microgrid without renewable generation or energy storage, and a 12% reduction ($65,800) compared to the ideal microgrid with renewable generation and electrical energy storage.

The developed algorithm is capable of being integrated into both isolated microgrids and grid-connected microgrids. It is also possible to consider a residential urban home as a form of microgrid. Although this does not fit into the classical definition of a microgrid because the residence is unable to operate independently of the grid, using control methods for residential loads creates the opportunity for homes to autonomously and intelligently vary their loads to the benefit of the system. This is more commonly considered smart load management. The developed algorithm could also be used for load management within this system.

A comparison is made between a system managed by the SMMS, and the equivalent system utilizing only battery energy storage to take advantage of arbitrage to determine if the additional cost of integrating the SMMS can be offset by its additional benefits. In each case, even when there was no differential in electricity pricing, the system managed by the SMMS has a payback period of less than 10 years, whereas the battery energy storage system does not have a payback period of less than 10 years, even when the price differential is as high as $0.15 / kWh.

In the development of the algorithm, it is seen that there are limitations to using thermal energy storage to act as an energy buffer in the home. There is never actually a decrease in energy consumption when using thermal storage, but rather only a deferral of energy. The total energy use of the home remains constant, and the financial benefit is solely based on the available pricing differential in the cost of energy.

In the case where loads, such as lighting, are shed during times deemed unnecessary, there is potential for financial benefit regardless of the energy pricing differential. Further methods of employing the SMMS can include communication with the owner, and further smart management of loads that are unnecessary at times, such as disconnecting appliances with phantom loads.

5. POWER SYSTEM RELIABILITY CONSIDERATIONS

5.1. Introduction

The studies carried out in the previous sections consider different combinations and capacities of power generation sources and energy storage facilities to meet the demand of the isolated microgrid. The level of reliability achieved with the different combinations can significantly vary, and a high level of reliability is usually associated with a relatively high system investment cost. Although the chief focus of this research project is to develop an SMMS that will reduce the cost of installing and operating a microgrid, it is important to determine the optimal system combination that provides a reasonable and acceptable level of system reliability. In the planning of small isolated power systems, deterministic reliability methods are generally applied that determine the capacity reserve margins that are required above the peak load of the system. These methods, however, do not recognize random system behavior, and therefore, are not suitable to microgrids that are supplied by intermittent generation from wind turbines and photovoltaics. Probabilistic methods that can model stochastic system behavior are more suitable for such systems. This section presents the development of a probabilistic model to assess the reliability of the different system scenarios discussed earlier, i.e. the base case system (generators only), the optimized base case system (generators and renewable energy, however energy storage has been removed), and the ideal microgrid (DSM, generators, renewable energy, and energy storage). The developed model is verified against an existing reliability program to ensure accuracy.

5.2. Methodology

Isolated communities are dependent upon fossil fuel generation to provide for their energy needs. Although fossil fuel generators are common and proven, communities require redundant systems to maintain reliability. It is the focus of this research project to develop an SMMS that manages DSM, energy storage, and renewable generation with the objective of maintaining the reliability of the isolated community at significantly reduced cost of operating the microgrid.

There are two predominant methods of assessing system reliability: analytical and simulation. To assess the reliability of the proposed systems, a simulation of the system is performed using Monte Carlo methods [62]. Monte Carlo methods simulate the actual process and functional operation of a system using random numbers.

The load and generation data employed to develop the most cost-effective combination of renewable generation, energy storage, load management, and conventional generation is analyzed from a reliability perspective to ensure an acceptable degree of reliability is achieved. A Sequential Monte Carlo Simulation (SMCS) is designed to estimate the reliability of the proposed system.

In order to verify the operation of the SMCS simulation model, the ideal microgrid base case without storage, demand side management, or PV generation is modeled in the program, and its reliability results is compared to the Small Isolated Power System Reliability [63] (SIPSREL) program, a program developed by the University of Saskatchewan to determine the loss of load expectation (LOLE) of power systems. SIPSREL was not designed to determine the reliability of a system with both battery and thermal energy storage, so it could not be used to assess the reliability of the optimized microgrid employing an SMMS.

The reliability parameters, mean time to failure (MTTF), and mean time to repair (MTTR) are specified based on operator information for the PV array, the propane generating unit, as well as the lithium-ion battery bank. Table 5.1 summarizes the MTTF and MTTR indices that are used for the reliability calculation. These parameters are used as inputs to the SMCS program developed in this project.

Table 5.1: Parameters for the Microgrid Technologies

Technology	**Rated Capacity**	**MTTF (hours)**	**MTTR (hours)**	**Equivalent Availability (%)**
Photovoltaic	30 kW	119,902	36	99.97%
Lithium Ion Energy Storage	25 kW / 50 kWh	2,400	6	99.75%
Propane Generator	25 kW	3,504	876	80.00%

Note that both the photovoltaic array and lithium-ion energy storage system largely consist of modular parts that can be easily replaced by non-trained persons. These components therefore have a relatively high reparability resulting in reduced downtime. The modular design also allows the systems to continue operating at derated states if part of the system fails. Although propane generators located close to service technicians have a relatively low MTTR, the data stated in Table 5.1 is indicative of an isolated community which would require a technician to travel to site with parts to repair the generator.

Each iteration of the SMCS model simulates five years of load and generation profiles, and uses MTTF and MTTR indices to determine generation 'up' and 'down' states throughout the simulation using Equations (5.1) and (5.2).

$$t_{up} = -MTTF \ln(Rand) \qquad (5.1)$$

$$t_{down} = -MTTR \ln(Rand) \qquad (5.2)$$

Where,

t_{up} = Generator 'up' time or normal operating time

t_{down} = Generator 'down' time

MTTF = Mean time to failure

MTTR = Mean time to repair

Rand = Randomly generated number between 0 and 1

Convergence criteria is defined to determine an appropriate stop time for the SMCS simulation. Each simulated iteration produces a unique loss of load expectation (LOLE). The deviation of the running average of the LOLE for the current iteration must be within a certain range of the running average for the previous iteration to establish convergence. The convergence criteria for this model is defined as a deviation not greater than 0.1% of the average LOLE for 50 consecutive iterations.

5.3. Results

To verify the SMCS model, the base case system consisting of two propane generators is modelled using the SMCS model and the SIPSREL program. Figure 5.1 indicates the convergence of the LOLE index as a function of iterations performed for the developed SMCS model. The

LOLE of the microgrid with two propane generators satisfying the “N-1” criterion meets the convergence criteria within 1358 iterations, and the LOLE of the system is found to be 348.04 hours / year. This model consists of two 25 kW propane generators and the load is comprised of the 5-home community with a peak demand of 25 kW and an annual energy consumption of 69,033 kWh. This value of LOLE is considered to be an acceptable reliability criterion as it corresponds to the conventionally accepted deterministic “N-1” criterion. In comparison, the SIPSREL program yields an LOLE of 351.32 hours / year for the same system. This is a difference of only -0.93%, which verifies the accuracy of the developed SMCS model when propane generators were the only source of generation.

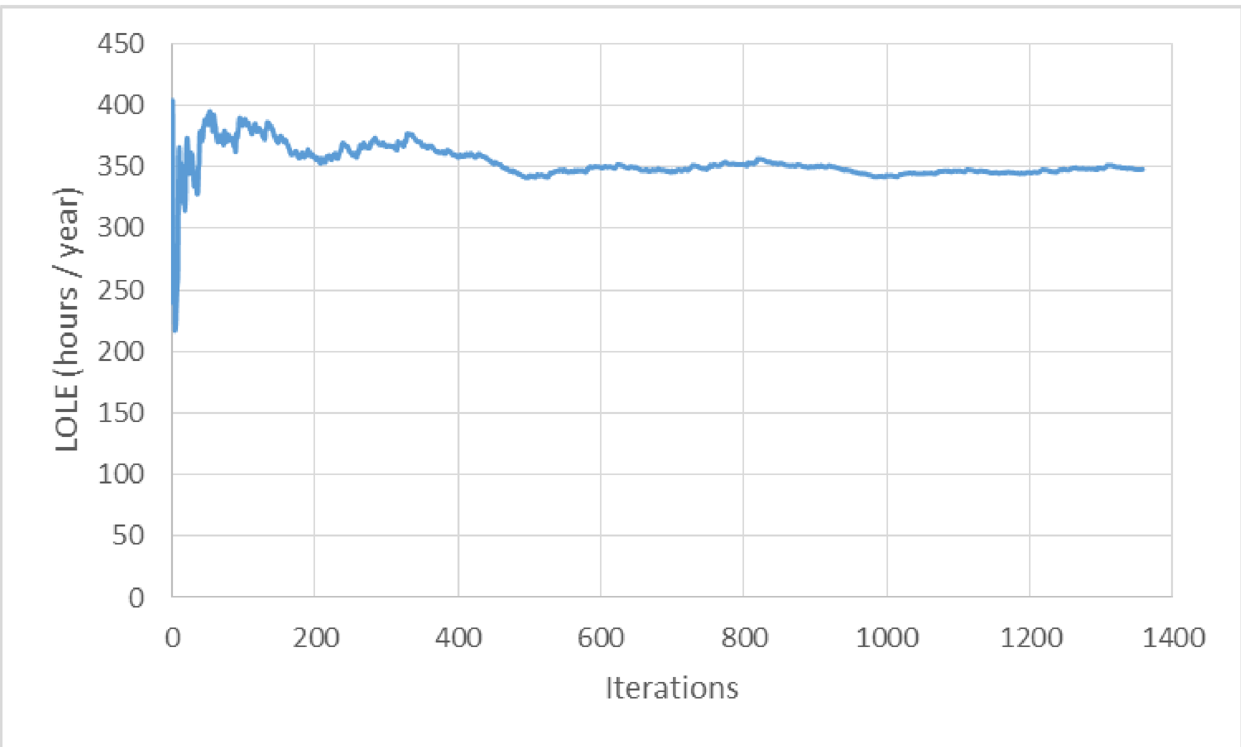

Figure 5.1: Average LOLE for the Base Case Microgrid with Two Propane Generators

To further verify the operation of the SMCS model, the solar generation profile is incorporated into the system, and its results are compared to the SIPSREL program. Before the power system can be analyzed in SIPSREL, PV generation data was reduced to a generation table to allow for input in to SIPSREL. To retain the seasonal and diurnal characteristics of the PV profile and its correlation to the load profile, PV generation data is separated into the following four categories:

- Winter Day
- Winter Night
- Summer Day
- Summer Night

Each day-time period consists of the time from 8:00 am to 8:00 pm, and the corresponding night-time period is from 8:00 pm to 8:00 am.

Sturges' Rule [64] is implemented to determine the least number of class intervals required to reduce the amount of load and generation data to be used in SIPSREL. Sturges' Rule is given in Equation (5.3).

$$NoCl = 1 + 3.3\ log_{10}\,(\mathrm{N}) \qquad (5.3)$$

where,

NoCl = Number of classes

N = Number of data points considered, equal to 8735 in the winter and 8783 in the summer

Based on Sturges' Rule, the required number of class intervals to represent the PV generation profile are indicated in Table 5.2 for each time period.

Table 5.2: Number of Classes Required by Sturges' Rule

Period	**Months**	**Annual Data Points**	**Required Classes**
Winter Day	October - March	8735	14.01
Winter Night	October - March	8735	14.01
Summer Day	April - September	8783	14.01
Summer Night	April - September	8783	14.01

Although Sturges' Rule indicated that each profile period can be reduced to 15 classes, the night-time PV generation data consists mostly of '0' kW of generation. Hence, only five classes are used to represent night time PV generation. The class size for each class interval is evenly distributed over the generation range of the PV array.

Tables 5.3 through 5.6 indicate the PV generation table and associated class intervals for each of the periods.

Table 5.3: PV Generation Table for the Winter Day-Time Period

Solar kW	**Probability**
0.0000	0.4304
1.1075	0.0900
3.3224	0.0950
5.5373	0.0563
7.7522	0.0391
9.9671	0.0350
12.1820	0.0307
14.3970	0.0279
16.6119	0.0302
18.8268	0.0327
21.0417	0.0272
23.2566	0.0284
25.4715	0.0250
27.6864	0.0286
29.9014	0.0192
32.1163	0.0041

Table 5.4: PV Generation Table for the Winter Night-Time Period

Solar Generation (kW)	**Probability**
0.0000	0.9982
0.0657	0.0002
0.1970	0.0002
0.3284	0.0009
0.4597	0.0005

Table 5.5: PV Generation Table for the Summer Day-Time Period

Solar kW	**Probability**
0.0000	0.4304
1.1075	0.0900
3.3224	0.0950
5.5373	0.0563
7.7522	0.0391
9.9671	0.0350
12.1820	0.0307
14.3970	0.0279
16.6119	0.0302
18.8268	0.0327
21.0417	0.0272
23.2566	0.0284
25.4715	0.0250
27.6864	0.0286
29.9014	0.0192
32.1163	0.0041

Table 5.6: PV Generation Table for the Summer Night-Time Period

Solar Generation (kW)	**Probability**
0.0000	0.8921
0.8499	0.0505
2.5497	0.0351
4.2496	0.0168
5.9494	0.0043
7.6492	0.0007
9.3490	0.0005

Note that in the Winter Night and the Summer Night periods, the peak PV generation observed over the entire period is only 0.53 kW, and 10.20 kW respectively.

Figure 5.2 indicates that convergence criteria is met within 1,358 iterations using the SMCS model for the optimized microgrid consisting of generators and a photovoltaic array, and the associated LOLE of the system is 249.83 hours / year. This model consists of two redundant 25 kW propane generators, and one 35 kW solar array. The load is comprised of the 5-home community with a peak demand of 25 kW and an annual energy consumption of 69,033 kWh. The same system is modelled using SIPSREL and the resultant reliability is 267.74 hours / year, a difference of only -6.69%. Although this difference is higher than the generator-only model comparison, this is still within acceptable error considering the variability of introducing the solar model into the SIPSREL program and the pre-processing that is required to reduce the photovoltaic generation to a 4-part generation table. Thus, the accuracy of the SMC model is once again verified.

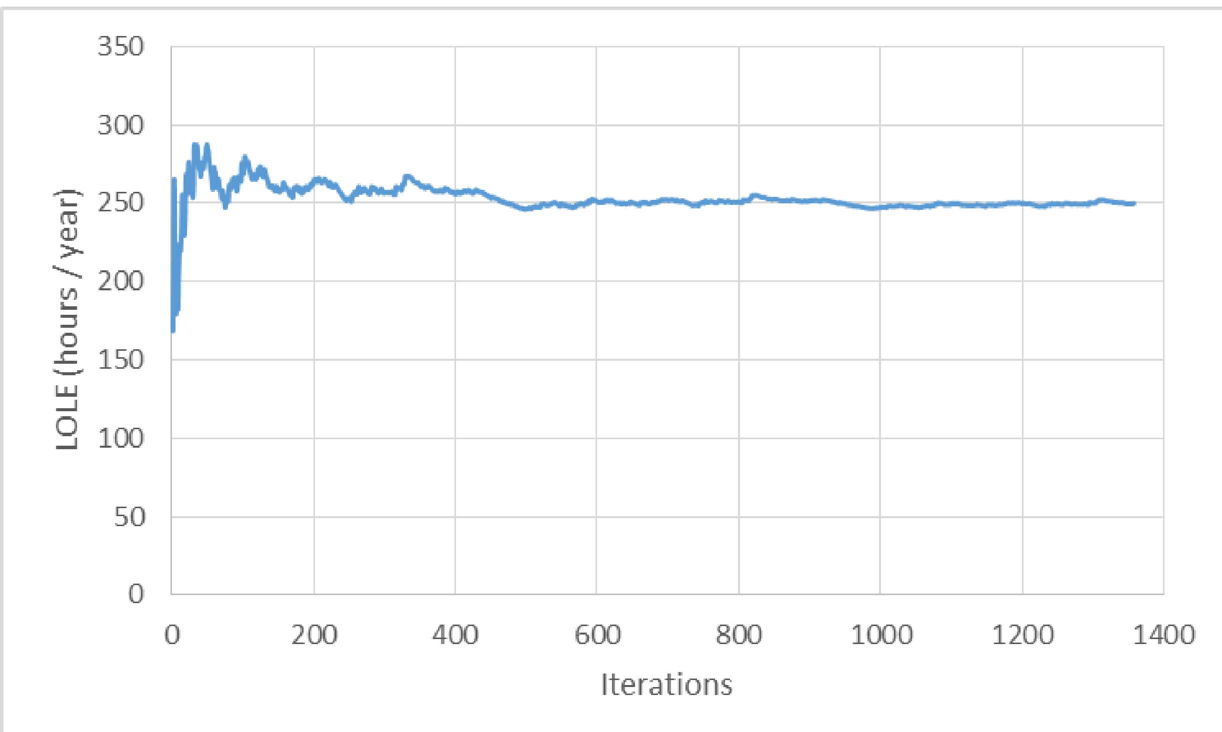

Figure 5.2: Average LOLE for Microgrid Consisting of Generators and PV

Table 5.7 summarizes the comparison between the results of the SIPSREL program and SMCS model that was developed for this research project.

Table 5.7: SIPSREL vs SMCS LOLE Comparison

	LOLE (hours/year)		
	SIPSREL	**SMCS**	**Difference**
Generators Only	351.32	348.04	-0.93%
Generators and Solar	267.74	249.83	-6.69%

For both cases where the SMCS model is compared to the SIPSREL program, the calculated LOLE is within acceptable error, and verifies the accuracy of the SMCS model. With the functionality of the SMCS model verified, the reliability of the ideal microgrid complete with demand side management techniques and energy storage devices can be assessed, since the SIPSREL program was unable to assess the reliability of the system when energy storage techniques are being implemented.

As previously indicated, the MTTF and MTTR for the battery energy storage system is estimated to be 2,400 hours and 6 hours respectively based on operator information. Although the actual MTTR for the battery as a whole would be greater than 6 hours, battery systems have a modular design which allows for battery strings to be automatically disconnected and isolated which enables the battery to continue operating at a slightly derated state. The operator is then able to change the module at a later time. Since the derated state resident time is significantly less than the up time, it has negligible impact on the results and is therefore ignored. Unskilled labour can be used to place the system in a derated state in order to continue operation of the energy storage system, thus increasing its overall ‘up time’.

The ideal microgrid's load, generation, and electrical and thermal storage profiles are used in the SMCS model to determine the system reliability of the ideal microgrid being managed by the SMMS. The system consists of two redundant 25 kW propane generators, one 30 kW solar array, one 25 kW / 50 kWh battery, and in-home thermal storage equivalent to a total of 4.81 kW / 21.85 kWh. Convergence occurs within 1,378 iterations, and yields an LOLE if 171.39 hours / year, as indicated in Figure 5.3. This value is lower than the LOLE of 248 hours / year. This indicates that the microgrid managed by SMMS can carry a system load higher than the existing load and still meet the acceptable reliability.

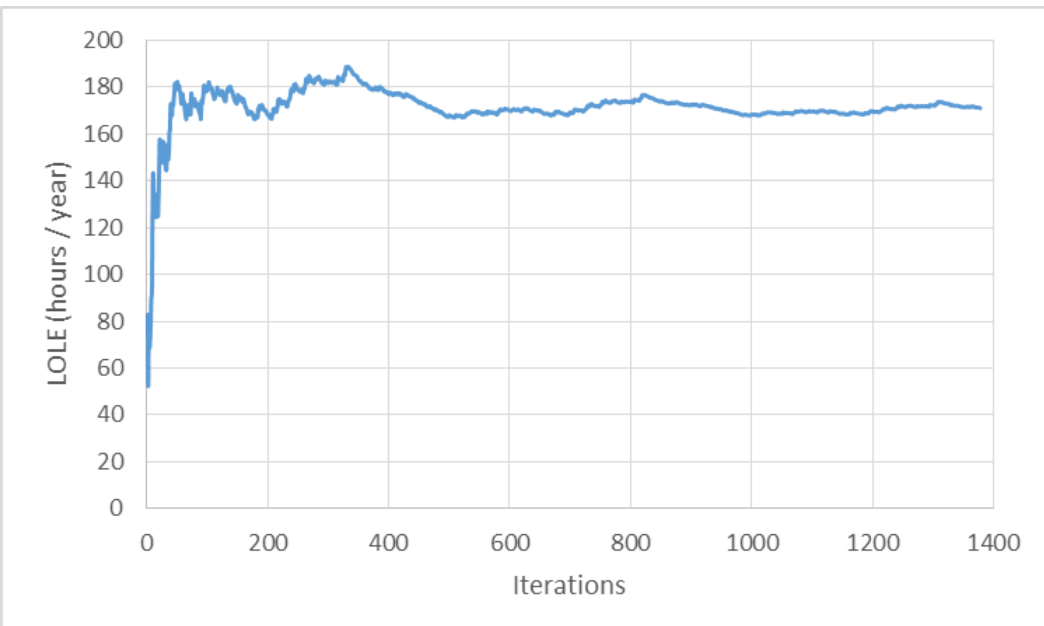

Figure 5.3: Average LOLE for Optimized Microgrid with an SMMS

5.4. Summary

The accuracy of the computer program developed based on the SMCS model is verified against the existing SIPSREL program for calculating LOLE. The calculated LOLE of the base case microgrid consisting only of generators is 348.04 hours / year. When a 35 kW photovoltaic array is added to the base case system, the LOLE of the system is reduced to 249.83 hours / year, which is 28.2% less than the base case. This is a result of the photovoltaic array being able to support the microgrid community at times when the generators is not functional. Once 25 kW / 50 kWh of battery energy storage, 30 kW of photovoltaics, 4.81 kW / 21.85 kWh of in-home thermal storage, and 0.355 kW of CLS are utilized via the SMMS, the LOLE is further reduced to 171.39 hours / year, which is 50.8% less than the base case, and 31.4% less than the optimized grid with photovoltaics. This is as expected, and is the result of using a combination of curtailable load shedding and stored energy during times when the generation components are not online in order to maintain microgrid functionality. By utilizing a combination of existing thermal storage located in the homes and load curtailment, the electrical energy storage system has an extended ability to support loads in the event of an outage. Table 5.8 summarizes the calculated LOLE values for each microgrid analyzed, and although the LOLE values are significantly higher than typical values in large power systems, the improvement in reliability of isolated systems should be justified by the additional associated costs to lower the LOLE values.

Table 5.8: Summary of LOLE Results

Configuration	**LOLE (hours / year)**	**Difference from Base Case (%)**
Generators Only (Base Case), Meeting the “N-1” Criterion	348.04	0
Generators and PV	249.83	-28.2%
Generators, PV, Energy Storage, and Curtailment	171.39	-50.8%

6. Summary and Conclusions

The objectives of this study, as defined by the industry partner and stated in Chapter 1, are to determine the load characterization of a 5-home microgrid and specify an optimized base case microgrid consisting of energy storage, generation, and loads. Once the optimized base case is established, a conceptual design for a smart microgrid management system (SMMS) is developed, along with an operational methodology for curtailing and deferring in-home loads for the financial benefit of the system. An algorithm is then developed to model the operation of the SMMS to verify and substantiate the economic benefit of employing such a system. Lastly, the reliability of the microgrid operated by the SMMS is compared to the optimized base case microgrid as well as the microgrid when operated solely by propane generators to indicate the improvement in system reliability. These objectives are achieved in this study.

A 5-home community is characterized by real-time data gathered from homes within Saskatchewan. The diversified peak load of the cumulative community is 25 kW, and the average electrical consumption of the community is 13,807 kWh / home. The total energy consumption of the 5-home microgrid is 69,035 kWh / year. Although details are not made available regarding the individual homes due to privacy concerns, the average energy consumption of the homes in the microgrid closely match a residence located near Saskatoon which operates solely on electricity and has its own water supply, septic system, and ground source heat pump. This home is used as the basis for the development of the model and for defining the load characteristics of the homes in the microgrid.

In the case where the microgrid operates solely on propane generators, the cost of providing energy for the community over a 20-year period equates to $581,517, or approximately $29,000 /

year. This represents an annual cost of $5,815 to provide electricity to each home, and an energy cost of $0.42 / kWh. An algorithm is then developed to model the operation of the same microgrid with various amounts of energy storage, and renewable energy generation to define a combination of generation and storage that minimizes the lifetime operational cost of the microgrid. The resulting optimized base case microgrid consists of the addition of a 35 kW photovoltaic array, and 90 kWh of lithium-ion battery energy storage. The lifetime operational cost of the optimized base case microgrid is $475,366, which equates to $0.34 / kWh or 18% less than the cost of operating solely on diesel generators.

In Chapter 4, the methodology for the operation of the proposed algorithm is presented. The SMMS operates as a closed-loop feedback system, and curtails and defers curtailable loads as required to reduce the operational cost of the microgrid. A conceptual layout is presented and consists of a generation / load interconnection bus that could be managed by a load controller to charge or discharge storage devices, or manage the operation of the generation sources.

The opportunity to integrate in-home thermal storage into the SMMS is also considered and the characteristics of the thermal storage devices are defined. Although many opportunities exist for controlling thermal energy storage in an average home, the most immediate opportunities which impacted residents the least are storing and depleting energy in the residents' domestic hot water tanks and ground source heat pump mass tanks.

The algorithm's flow chart is presented which indicates the SMMS' decision-making process based on real-time feedback from the microgrid system. As well, a conceptual design for the remote monitoring, control, and computing is shown along with proposed functionality and estimated costs.

A MATLAB program is developed that models the functionality of the SMMS algorithm. The algorithm analyzes various combinations of energy storage and generation sources to determine the most economically beneficial microgrid combination. The algorithm indicates that the most financially viable microgrid combination consists of a 30 kW photovoltaic array, and 25 kW / 50 kWh of lithium-ion battery storage. This represents a reduction in electrical energy storage of 45% and a reduction in renewable generation of 15% compared to the optimized base case microgrid combination presented earlier. The lifetime cost to operate the microgrid using the SMMS is $418,566 which represents a reduction of 12% compared to the optimized microgrid. The levelized cost of energy for the system managed by the SMMS is $0.30 / kWh. This proves that the additional 4.81 kW / 21.85 kWh of thermal storage and 0.355 kW of curtailable load shedding utilized by the SMMS improves the performance of the microgrid and reduces the cost of the system.

Another method of employing the SMMS can be to automate parts of the home that can help reduce the total required energy. This could include automating window shades and shutters, and running fans that bring cooler night air into the house during the summer to reduce daytime cooling loads. The SMMS could also allow instant messages to be sent to the home owner regarding methods that could be used to reduce home energy consumption based on feedback from the in-home systems, as well as generation components.

To ensure that the further reduction in operating cost offered by the SMMS is not offset by a reduction in power system reliability, a Sequential Monte Carlo Simulation (SMCS) is designed to analyze microgrid reliability. To ensure accuracy, the SMCS model is verified against the Small Isolated Power System Reliability (SIPSREL) program, developed by the University of Saskatchewan. Although SIPSREL can accurately determine the reliability of the base microgrid operating on propane generation and the optimized microgrid which employed renewable energy, it cannot analyze microgrids with an energy storage component. Thus, the SMCS model is depended upon to provide the power system reliability assessment for the system managed by the SMMS, but it is first verified against SIPSREL using the base case microgrid and the optimized base case microgrid. In both cases, the SMCS model agrees with the SIPSREL model within reason and verifies the operation of the SMCS model.

The SMCS model determines that the Loss of Load Expectation (LOLE) for the base case microgrid operating with two 25 kW redundant generators is 348.04 hours / year. The addition of a 35 kW photovoltaic array reduces the LOLE of the optimized base case microgrid to 249.83 hours / year. Lastly, utilizing 25 kW / 50 kWh of lithium-ion energy storage, 30 kW of photovoltaics, 4.81 kW / 21.85 kWh of in-home thermal storage and 0.355 kW of CLS, the LOLE of the microgrid managed by the SMMS is decreased to 171.39 hours / year, a reduction in LOLE of 31.4% and 50.8% compared to the optimized base case microgrid with photovoltaics and the base microgrid with only propane generation, respectively.

As power consumption continues to grow, and more communities and businesses require reliable power, the need for microgrids and distributed generation will continue to rise as the communities which do not currently have a connection to the utility grid are generally far-removed from utility grid boundaries. As well, the reduction in the cost of renewable generation and battery energy storage make enticing value propositions for the implementation of microgrids when compared to the cost of long transmission lines feeding remote communities which may have low reliability.

Recent initiatives around the world are focusing on a move to renewable energy in an effort to curb global climate change which is attributed to, in part, conventional fossil fuel generation sources. However, a move towards renewables does come at the cost of potential intermittency. This intermittency can be resolved by various solutions, including robust interconnection to neighboring utilities, fast-ramping generation sources, and energy storage. As prices for energy storage continue to fall, the inclusion of batteries in microgrids becomes increasingly financially viable, which further increases the viability of developing microgrids.

The microgrid system developed in this study yields a highly efficient method of generation, and has also increased the power system reliability of the proposed community.

The industry partner, the Saskatchewan Research Council, has considered the results of the study and has used some of the findings to develop a novel hybrid system to install at remote communities which can reduce diesel fuel consumption by up to 86%. The hybrid pilot project was installed at a remote mine remediation site in Northern Saskatchewan in the summer of 2015.

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APPENDIX - ANNUAL RESIDENTIAL LOAD PROFILES

The following figures display the annual time of day load profiles for the 5 residences analyzed in this study.

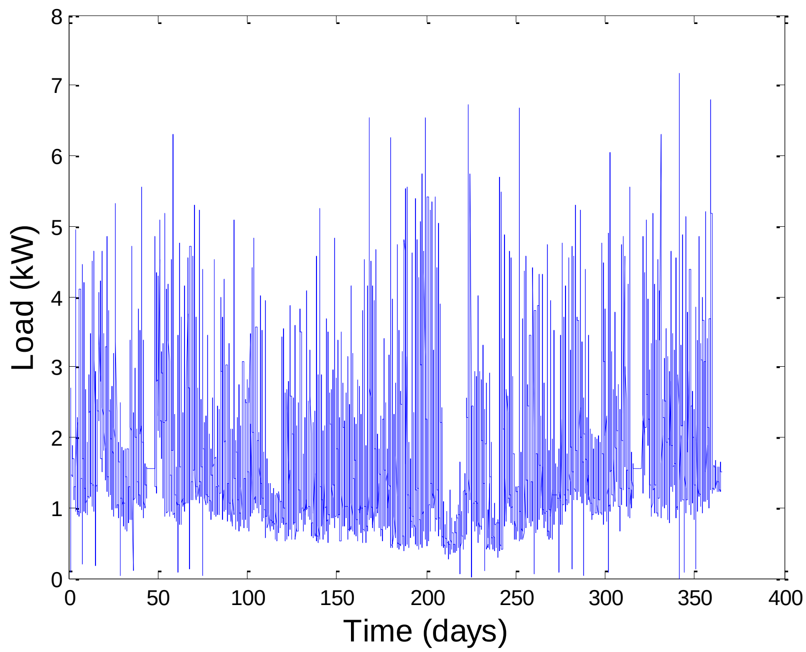

Figure A.1: Academy Residence Annual Load Profile

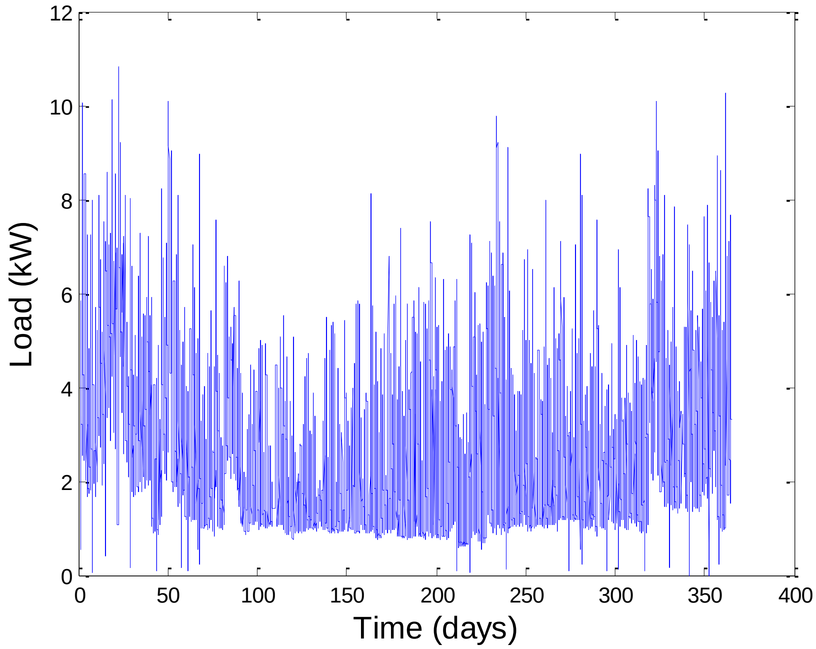

Figure A.2: Chatwin Residence Annual Load Profile

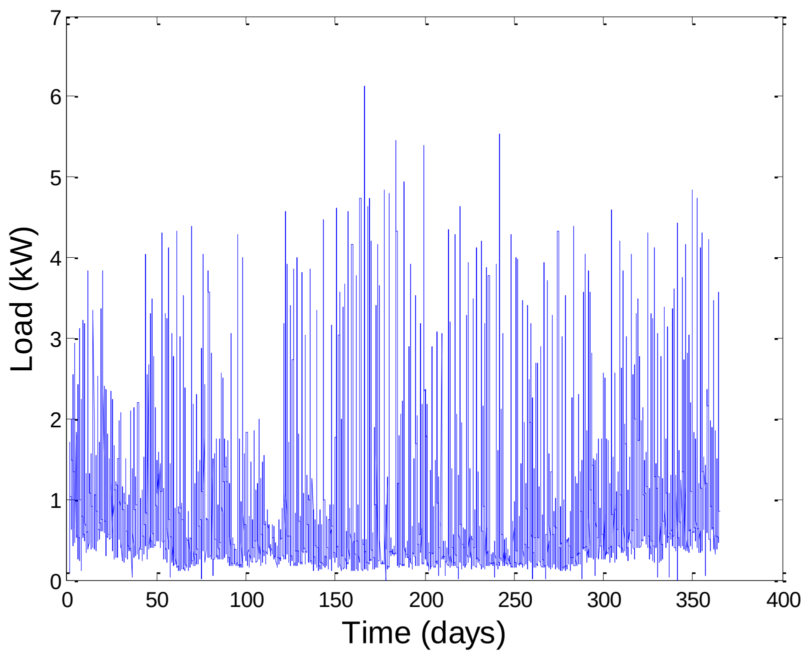

Figure A.3: Garnet Residence Annual Load Profile

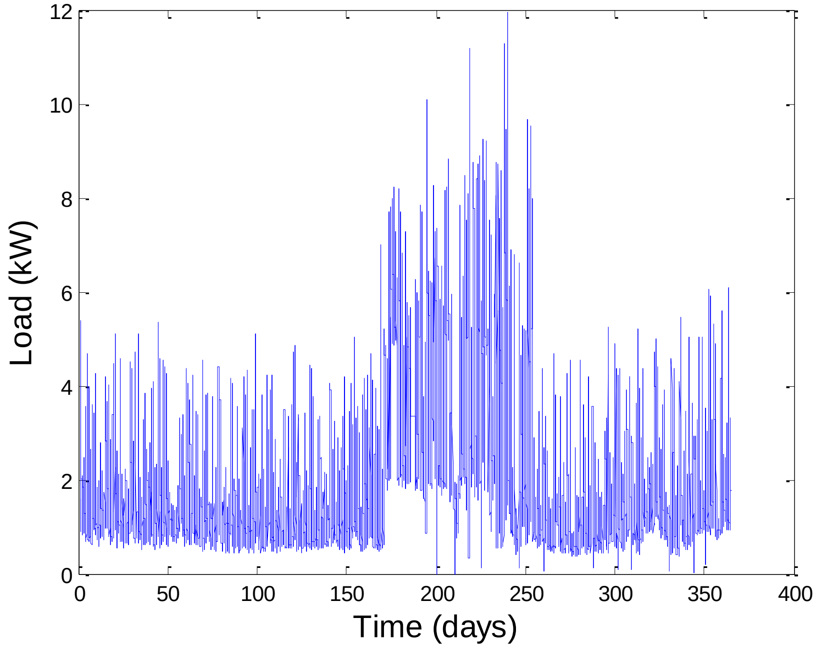

Figure A.4: Gregory Residence Annual Load Profile

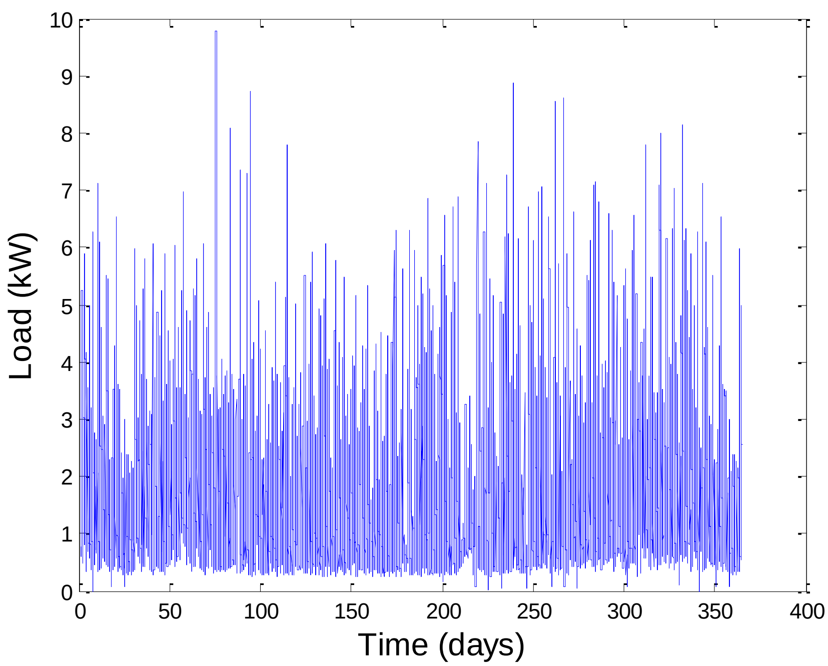

Figure A.5: Struthers Residence Annual Load Profile